

# Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: A retrospective analysis with a process-based biogeochemistry model

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[1] We develop and use a new version of the Terrestrial Ecosystem Model (TEM) to study how rates of methane (CH<sub>4</sub>) emissions and consumption in high-latitude soils of the Northern Hemisphere have changed over the past century in response to observed changes in the region's climate. We estimate that the net emissions of CH<sub>4</sub> (emissions minus consumption) from these soils have increased by an average 0.08 Tg CH<sub>4</sub> yr<sup>-1</sup> during the twentieth century. Our estimate of the annual net emission rate at the end of the century for the region is 51 Tg CH<sub>4</sub> yr<sup>-1</sup>. Russia, Canada, and Alaska are the major CH<sub>4</sub> regional sources to the atmosphere, responsible for 64%, 11%, and 7% of these net emissions, respectively. Our simulations indicate that large interannual variability in net CH<sub>4</sub> emissions occurred over the last century. Our analyses of the responses of net CH<sub>4</sub> emissions to the past climate change suggest that future global warming will increase net CH<sub>4</sub> emissions from the Pan-Arctic region. The higher net CH<sub>4</sub> emissions may increase atmospheric CH<sub>4</sub> concentrations to provide a major positive feedback to the climate system.

**INDEX TERMS:** 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805); 1620 Global Change: Climate dynamics (3309); 1890 Hydrology: Wetlands; **KEYWORDS:** methane emissions, methane oxidation, permafrost

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## 1. Introduction

[2] Soils have the capacity to both produce and consume methane (CH<sub>4</sub>), a powerful greenhouse gas. A special group of soil microorganisms, the methanogens, is responsible for CH<sub>4</sub> production, while another group, the methanotrophs, is responsible for CH<sub>4</sub> consumption. Recent estimates put CH<sub>4</sub> emissions from the world's soils at between 150 and 250 Tg CH<sub>4</sub> yr<sup>-1</sup> [Prather *et al.*, 2001], with a quarter to a third of the total emitted from the wet soils of high latitudes [Walter *et al.*, 2001a]. Estimates of CH<sub>4</sub> consumption by soil microbes are in the range of 10–30 Tg CH<sub>4</sub> yr<sup>-1</sup> [Prather *et al.*, 2001], an order of magnitude lower than the emission estimates. Most of the CH<sub>4</sub> consumption occurs in the well-drained soils of temperate and tropical areas [Ridgwell *et al.*, 1999].

[3] Terrestrial ecosystems north of 45°N have experienced earlier and more dramatic environmental changes from global warming compared with lower-latitude ecosystems, especially in the last decades of the twentieth century. These changes include higher mean annual air temperatures, increases in precipitation, and melting of permafrost [Romanovsky *et al.*, 2000; Vitt *et al.*, 2000; Prather *et al.*, 2001]. The warmer temperatures and the alterations of hydrology in the region have resulted in changes in the magnitude and timing of CH<sub>4</sub> emissions and consumption [e.g., Friborg *et al.*, 1997; Whalen and Reeburgh, 1992; West and Schmidt, 1998]. For example, larger CH<sub>4</sub> emissions have been observed earlier during the year that are associated with earlier spring thaws in sub-arctic mire ecosystems [e.g., Friborg *et al.*, 1997]. Larger CH<sub>4</sub> emissions have also been associated with increases in the thickness of the active layer in permafrost zones [Whalen and Reeburgh, 1992; Moore *et al.*, 1990; Dise, 1993].

[4] Many of the regional and global estimates of CH<sub>4</sub> fluxes between the land and the atmosphere have been based on limited site measurements and simple extrapolation procedures [e.g., Whalen and Reeburgh, 1990b; Whalen *et al.*, 1991]. Recently, several large-spatial-scale models [e.g., Cao *et al.*, 1996; Liu, 1996; Potter *et al.*, 1996; Prinn *et al.*, 1999; Ridgwell *et al.*, 1999; Walter and Heimann, 2000; Walter *et al.*, 2001a, 2001b] have been

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developed to estimate current and future methane exchanges between the land and the atmosphere. These models have incorporated many of the factors that control  $\text{CH}_4$  fluxes and have led to major advances in our understanding of  $\text{CH}_4$  fluxes to the atmosphere from northern ecosystems. However, the existing models have not considered the complex behavior of the freeze-thaw phenomena, i.e., the freezing of soil upward from the permafrost boundary as well as downward from the soil surface [see Zhuang *et al.*, 2001; Goodrich, 1978a, 1978b], in northern ecosystems when developing their estimates. We build on this solid foundation by explicitly considering the effects of permafrost freeze-thaw dynamics and vegetation carbon dynamics on the consumption and emissions of methane from soils.

[5] To estimate  $\text{CH}_4$  fluxes between soils and the atmosphere, we have developed a new methane module and have coupled it to our process-based biogeochemistry model, the Terrestrial Ecosystem Model (TEM) [Melillo *et al.*, 1993; Zhuang *et al.*, 2003]. We use this model to estimate the “net  $\text{CH}_4$  emissions” (i.e., emissions minus consumption) from the region north of  $45^\circ\text{N}$  during the 1990s. We then use the model to explore how these net  $\text{CH}_4$  emissions have changed from 1900 to 2000.

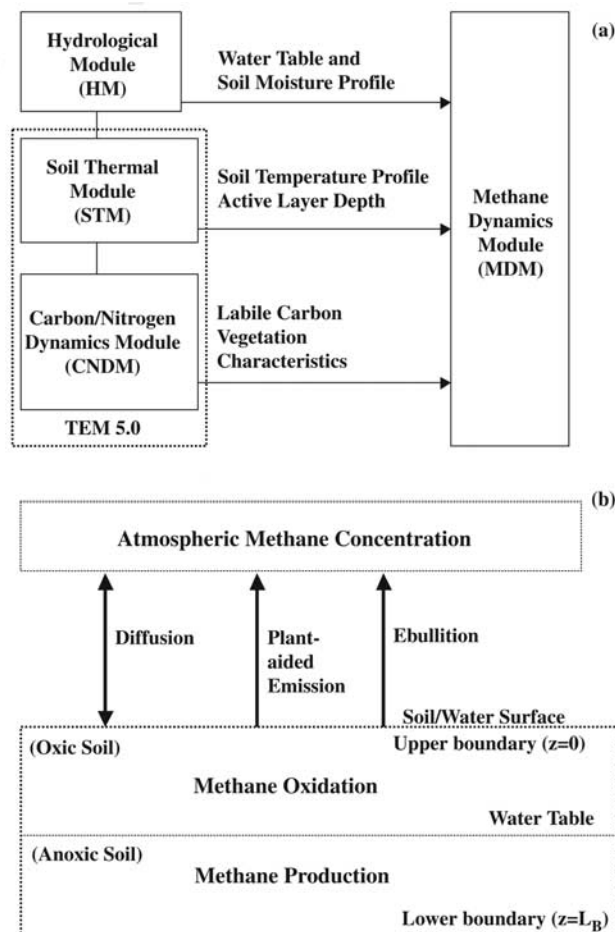
## 2. Methods

### 2.1. Model Framework

[6] We have developed an hourly time step methane dynamics module (MDM) for TEM that explicitly considers the process of  $\text{CH}_4$  production (methanogenesis) as well as  $\text{CH}_4$  oxidation (methanotrophy) and the transport of the gas from the soil to the atmosphere. We have coupled the MDM with several existing TEM modules (Figure 1a): the core carbon and nitrogen dynamics module of TEM 5.0 (CNDM) [Zhuang *et al.*, 2003], the soil thermal module (STM) that includes permafrost dynamics [Zhuang *et al.*, 2001], and an improved and expanded hydrological module (HM) [Zhuang *et al.*, 2002] that simulates water movement across an atmosphere-vegetation-soil continuum. For northern ecosystems, the soil component of the HM considers moisture dynamics explicitly in moss, organic soil, and mineral soil layers [Zhuang *et al.*, 2002], and is designed to consider fluctuations in water table depth.

#### 2.1.1. Methane Dynamics Module

[7] Fluxes of methane between soils and the atmosphere depend on the relative rates of methane production and oxidation within the soil profile and the transport of methane across the surface of soils. We assume that soils can be separated into an upper unsaturated zone and a lower saturated zone according to the water table depth. Methanotrophy (methane oxidation) occurs in the unsaturated zone and methanogenesis (methane production) occurs in the saturated zone. Because methanotrophy reduces soil methane concentrations in the unsaturated zone and methanogenesis increases soil methane concentrations in the saturated zone, the resulting concentration gradient causes methane to diffuse from the saturated zone into the unsaturated zone. If the rate of methanogenesis is larger than the rate of methanotrophy within the soil profile, such as occurs in wetland soils, methane will be emitted to the atmosphere



**Figure 1.** Schematic diagram of the new version of a biogeochemistry model (TEM) including (a) the overall model structure which features a soil thermal module (STM) [Zhuang *et al.*, 2001], an updated hydrologic module (HM) based on Zhuang *et al.* [2002], a carbon/nitrogen dynamics module (CNDM) from TEM 5.0 [Zhuang *et al.*, 2003], and a methane dynamics module (MDM); and (b) the more detailed structure of the MDM including the separation of soil into anaerobic and aerobic zones by water table position. The soil profile is divided into 1-cm layers that are referenced by their depth  $z$  from the upper boundary ( $z = 0$ ) to a lower boundary ( $L_B$ ,  $z > 0$ ). The rates of  $\text{CH}_4$  production and oxidation are determined with factors described in the text and Appendices A and B. The different transport pathways of  $\text{CH}_4$  between soils and the atmosphere (diffusion, plant-aided transport, and ebullition) are described in the text and in Appendix C.

through diffusion. There are two other pathways in addition to diffusion that can be important for  $\text{CH}_4$  transport to the atmosphere. Soil  $\text{CH}_4$  can be transported from deep layers in sediments and soils through “hollow tubes” running from the roots through the stems to the leaves of some plants (plant-aided transport). If the water table is above the soil surface, methane can also move in bubbles through the

**Table 1.** Parameters of the Methane Dynamics Module for Major Ecosystem Types in the Northern High Latitudes<sup>a</sup>

|                           | Alpine Tundra/Polar Desert         |                       | Moist/Wet Tundra      |                       | Boreal Forest        |                 | Unit                                 |
|---------------------------|------------------------------------|-----------------------|-----------------------|-----------------------|----------------------|-----------------|--------------------------------------|
|                           | Wetland<br>(Toolik-D) <sup>b</sup> | Upland<br>(Tundra-NS) | Wetland<br>(Toolik-W) | Upland<br>(Tundra-UI) | Wetland<br>(SSA-FEN) | Upland<br>(B-F) |                                      |
| $L_{\text{MAXB}}$         | 100                                | 100                   | 100                   | 100                   | 110                  | 100             | cm                                   |
| <i>Methanogenesis</i>     |                                    |                       |                       |                       |                      |                 |                                      |
| $M_{\text{GO}}$           | 0.45                               | 0.45                  | 1.0                   | 0.45                  | 1.3                  | 0.8             | $\mu\text{mol L}^{-1} \text{h}^{-1}$ |
| $\text{NPP}_{\text{MAX}}$ | 100                                | 100                   | 150                   | 100                   | 250                  | 250             | $\text{gC m}^{-2} \text{month}^{-1}$ |
| $P_{\text{Q10}}$          | 3.5                                | 3.5                   | 4.0                   | 3.5                   | 4.5                  | 7.5             | —                                    |
| $T_{\text{PR}}$           | −3.0                               | 8.0                   | −5.5                  | 8.0                   | 10.0                 | 7.0             | °C                                   |
| <i>Methanotrophy</i>      |                                    |                       |                       |                       |                      |                 |                                      |
| $O_{\text{MAX}}$          | 35                                 | 1.0                   | 30                    | 2.0                   | 15                   | 1.0             | $\mu\text{mol L}^{-1} \text{h}^{-1}$ |
| $K_{\text{CH4}}$          | 5.0                                | 10.0                  | 5.0                   | 5.0                   | 5.0                  | 15              | $\mu\text{mol L}^{-1}$               |
| $O_{\text{Q10}}$          | 3.5                                | 0.8                   | 2.2                   | 1.1                   | 1.9                  | 1.5             | —                                    |
| $T_{\text{OR}}$           | −3.0                               | 5.0                   | −5.5                  | 5.5                   | 10.0                 | 5.4             | °C                                   |
| $M_{\text{VMAX}}$         | 1.0                                | 0.9                   | 1.0                   | 0.7                   | 1.0                  | 1.0             | % volume                             |
| $M_{\text{VMIN}}$         | 0.0                                | 0.0                   | 0.0                   | 0.0                   | 0.0                  | 0.2             | % volume                             |
| $M_{\text{VOPT}}$         | 0.5                                | 0.4                   | 0.5                   | 0.3                   | 0.5                  | 0.6             | % volume                             |

<sup>a</sup>See text or notation section for the definition of variables.<sup>b</sup>Names in parentheses represent sites used to calibrate the methane dynamics module; see Table 2.

overlying water and escape to the atmosphere. This transport process is known as ebullition.

[8] If the rate of methanotrophy is greater than the rate of methanogenesis within the soil profile, then most, if not all, of the methane produced in the saturated zone will be oxidized in the unsaturated zone and little or no  $\text{CH}_4$  will be emitted from soils. Indeed, if the rate of methanogenesis is negligible, methanotrophy may cause a concentration gradient to develop that causes methane to diffuse from the atmosphere into the soil, such as occurs in well-drained upland soils. In this situation, soils are said to “consume” atmospheric methane.

[9] To simulate methane dynamics within the soil, we divide the soil column into a layered system with 1-cm increments from an upper boundary (i.e., the soil surface or water surface if the water table is above the soil surface) to a lower boundary ( $L_B$ ), which represents the depth of microbial activity (Figure 1b). The  $L_B$  depends on active layer (i.e., unfrozen soil) depth as simulated by the soil thermal module. If the active layer depth is deeper than the maximum depth of microbial activity prescribed for an ecosystem ( $L_{\text{MAXB}}$ ; see Table 1), the  $L_B$  is equal to  $L_{\text{MAXB}}$ ; otherwise the  $L_B$  is equal to the active layer depth.

[10] Within each soil layer, changes in  $\text{CH}_4$  concentration are governed by the following equation:

$$\frac{\partial C_M(z, t)}{\partial t} = M_P(z, t) - M_O(z, t) - \frac{\partial F_D(z, t)}{\partial z} - R_P(z, t) - R_E(z, t), \quad (1)$$

where  $C_M(z, t)$  is the soil  $\text{CH}_4$  concentration in  $\mu\text{mol L}^{-1}$  at depth  $z$  (centimeters) and time  $t$  (time step = 1 hour),  $M_P(z, t)$  is the  $\text{CH}_4$  production rate,  $M_O(z, t)$  is the  $\text{CH}_4$  oxidation rate,  $R_P(z, t)$  is the plant-aided  $\text{CH}_4$  emissions rate, and  $R_E(z, t)$  is the ebullitive  $\text{CH}_4$  emissions rate. The term,  $\frac{\partial F_D(z, t)}{\partial z}$ , the flux divergence, represents the net change in methane concentration resulting from the diffusion of methane into soil layer  $z$  from the surrounding soil layers or the atmosphere (if  $z = 0$ ) and the diffusion of methane out of soil layer

$z$  into the other soil layers or the atmosphere (if  $z = 0$ ). The rates of diffusion and the emissions calculated for each soil layer within the soil profile are then used to determine the  $\text{CH}_4$  flux at the soil or water surface. The  $\text{CH}_4$  flux between the atmosphere and the soil ( $F_{\text{CH}_4}(t)$ ) is the total of the fluxes at the soil/water-atmosphere boundary via the different transport pathways,

$$F_{\text{CH}_4}(t) = F_D(z = 0, t) + F_P(t) + F_E(t), \quad (2)$$

where  $F_D(z = 0, t)$  is the diffusive flux of  $\text{CH}_4$  between the atmosphere and the soil surface,  $F_P(t)$  is the sum of all the plant-aided  $\text{CH}_4$  emissions, and  $F_E(t)$  is the sum of all the ebullitive  $\text{CH}_4$  emissions. By numerically solving equation (1) for all the soil layers simultaneously, we obtain  $F_D(z = 0, t)$  which will be positive if methane diffuses from the soil out to the atmosphere and will be negative if methane diffuses from the atmosphere into the soil. We determine  $F_P(t)$  by integrating  $R_P(z, t)$  for all soil layers between the soil surface and the rooting depth. Similarly,  $F_E(t)$  is obtained by integrating  $R_E(z, t)$  over all soil layers in the saturated zone if the water table is at or above the soil surface. Otherwise, the  $F_E(t)$  term will equal 0.0. Emissions of  $\text{CH}_4$  from soils occur when  $F_{\text{CH}_4}(t)$  is positive and  $\text{CH}_4$  consumption by soils occurs when  $F_{\text{CH}_4}(t)$  is negative.

[11] As both biological activity and soil transport properties influence our estimates of  $\text{CH}_4$  fluxes at the soil/water surface, we describe below how we obtain the terms in equation (1) in more detail.

#### 2.1.1.1. Methane Production

[12] Methane production is modeled as an anaerobic process that occurs in the saturated zone of the soil profile. We estimate hourly methanogenesis ( $M_P(z, t)$ ) within each 1-cm layer of the soil profile as follows:

$$M_P(z, t) = M_{\text{GO}} f(S_{\text{OM}}(z, t)) f(M_{\text{ST}}(z, t)) f(\text{pH}(z, t)) f(R_X(z, t)), \quad (3)$$

where  $M_{\text{GO}}$  is the ecosystem-specific maximum potential production rate (Table 1);  $f(S_{\text{OM}}(z, t))$  is a multiplier that enhances methanogenesis with increasing methanogenic



substrate availability, which is a function of net primary production of the overlying vegetation;  $f(M_{ST}(z, t))$  is a multiplier that enhances methanogenesis with increasing soil temperatures using a  $Q_{10}$  function [Walter and Heimann, 2000] with  $Q_{10}$  coefficients ( $P_{Q10}$ ) and reference temperatures ( $T_{PR}$ ) that vary across ecosystems (Table 1);  $f(pH(t))$  is a multiplier that diminishes methanogenesis if the soil-water pH is not optimal (i.e., pH = 7.5) as described by Cao *et al.* [1996]; and  $f(R_X(z, t))$  is a multiplier that describes the effects of the availability of electron acceptors which is related to redox potential on methanogenesis. To simulate  $f(R_X(z, t))$ , we use the relationships of Zhang *et al.* [2002] and Fiedler and Sommer [2000] where  $f(R_X(z, t))$  diminishes methanogenesis linearly if redox potential is greater than  $-200$  mV; otherwise,  $f(R_X(z, t))$  is equal to 1.0. With the exception of  $f(S_{OM}(z, t))$  which is described in section 2.1.4, the components of equation (3) are described in more detail in Appendix A.

### 2.1.1.2. Methane Oxidation

[13] Methane oxidation is modeled as an aerobic process that occurs in the unsaturated zone of the soil profile. We estimate hourly methanotrophy ( $M_O(z, t)$ ) within each 1-cm layer of the soil profile as follows:

$$M_O(z, t) = O_{MAX} f(C_M(z, t)) f(T_{SOIL}(z, t)) f(E_{SM}(z, t)) f(R_{OX}(z, t)), \quad (4)$$

where  $O_{MAX}$  is the ecosystem-specific maximum oxidation coefficient (Table 1) that typically ranges between 0.3 and  $360 \mu\text{mol L}^{-1} \text{h}^{-1}$  [Segers, 1998];  $f(C_M(z, t))$  is a multiplier that enhances methanotrophy with increasing soil methane concentrations using a Michaelis-Menten function with a half-saturation constant ( $K_{CH_4}$ ) that varies across ecosystems (Table 1);  $f(T_{SOIL}(z, t))$  is a multiplier that enhances methanotrophy with increasing soil temperatures using a  $Q_{10}$  function [Walter and Heimann, 2000] with  $Q_{10}$  coefficients ( $O_{Q10}$ ) and reference temperatures ( $T_{OR}$ ) that vary across ecosystems (Table 1);  $f(E_{SM}(z, t))$  is a multiplier that diminishes methanotrophy if the soil moisture is not at an optimum level ( $M_{vopt}$ ); and  $f(R_{OX}(z, t))$  is a multiplier that enhances methanotrophy as redox potentials increase linearly from  $-200$  mV to  $200$  mV [Zhang *et al.*, 2002]. As redox potentials become greater than  $200$  mV,  $f(R_{OX}(z, t))$  is set equal to 1.0. Methanotrophy is also assumed to cease if soil moistures reach a critical minimum ( $M_{vmin}$ ) or maximum ( $M_{vmax}$ ) soil moisture. These critical soil moistures along with the optimum soil moisture ( $M_{vopt}$ ) are assumed to vary among ecosystems (Table 1). The components of equation (4) are described in more detail in Appendix B.

[14] The inputs to equations (3) and (4) are either prescribed for a site or provided by the other modules of the coupled model. Net primary production (NPP) is estimated by the CNDM. Soil temperatures are provided by the STM. Soil-water pH is prescribed for a site. Redox potential is calculated based on root distribution, the fraction of water-filled pore space, and the position of the water table [Zhang *et al.*, 2002; Segers and Kengen, 1998]. Root distribution is prescribed for a site based on ecosystem type. The fraction

of water-filled pore space, the position of the water table, and soil moisture are provided by the HM.

### 2.1.1.3. Methane Transport

[15] In the model, we consider three pathways by which  $\text{CH}_4$  can be transported from the site of production in wetlands to the atmosphere: (1) diffusion through the soil profile ( $F_D(z, t)$ ); (2) plant-aided transport ( $R_P(z, t)$ ); and (3) ebullition ( $R_E(z, t)$ ). In upland soils, we assume that diffusion of atmospheric methane into soils is the sole method of moving methane through the soil. We assume that soil diffusion follows Fick's law with a diffusion coefficient that varies with soil texture [Walter *et al.*, 2001a] and moisture status (i.e., saturated or unsaturated) of the soil layers [Walter and Heimann, 2000]. Plant-aided transport depends on vegetation type, plant density, the distribution of roots in the soil, and soil  $\text{CH}_4$  concentrations [Walter and Heimann, 2000]. Ebullition occurs in saturated soil layers where the  $\text{CH}_4$  concentration is greater than  $500 \mu\text{mol L}^{-1}$  to allow bubbles to be formed [Walter and Heimann, 2000].

[16] The amount and timing of  $\text{CH}_4$  emissions depend on the pathway used to transport methane to the atmosphere. Diffusion is relatively slow such that  $\text{CH}_4$  produced in the lower saturated zone may be oxidized in the unsaturated zone before it can reach the atmosphere. In contrast, methane emissions from plant-aided transport or ebullitions, if the water table is at or above the soil surface, may reach the atmosphere from anywhere in the soil profile in a single hourly time step. However, if the water table is below the soil surface, bubbles formed in the saturated zone will contribute methane to the soil layer just above the water table. This methane will then continue to diffuse upward in the unsaturated zone where it may also be oxidized before reaching the atmosphere. Similar to Walter and Heimann [2000], we also assume that a portion of the methane transported by plants will be oxidized before the gas reaches the atmosphere. However, we assume that only 40 percent of the methane is oxidized as compared to the 50 percent assumed by Walter and Heimann [2000]. We describe how we modeled each of these transport pathways in more detail in Appendix C.

### 2.1.2. Soil Thermal Module

[17] The soil thermal module (STM) [Zhuang *et al.*, 2001, 2002, 2003] is used to estimate the active layer depth (i.e., the depth of unfrozen soil that varies seasonally) and soil temperatures at specified depths within the soil profile based on monthly or daily air temperatures and precipitation. In the module, the vertical profile is divided into six thermal layers: snowpack, moss (or litter), upper organic soil, lower organic soil, upper mineral soil, and lower mineral soil. Each of these thermal layers is characterized with a distinct soil thermal conductivity and heat capacity. The module considers two freezing fronts: (1) a front where soil freezes upward from the permafrost boundary and (2) a front where soil freezes downward from the ground surface. For the snowpack layer, a snow classification system [Liston and Pielke, 2000] has been implemented to better characterize the effect of seasonal changes in snow density and thermal conductivity within various ecosystems on the soil thermal regime at a large spatial scale. The soil thermal module has been designed to run at a flexible time step (e.g., 0.5 hour,

0.5 day) and several depth steps (e.g., 2 cm, 5 cm). The module has been calibrated and validated for major biomes in the Northern Hemisphere [Zhuang *et al.*, 2001, 2002] and the globe [Zhuang *et al.*, 2003].

[18] In this study, the methane dynamics module (MDM) requires the input of soil temperatures at each 1 cm depth of the soil layer in addition to the active layer depth. Therefore we use the STM to simulate the soil temperatures for a limited number of depths within the organic and mineral soil layers due to computational time constraints. The daily soil temperatures at each 1 cm depth are then obtained through linear interpolation of the daily soil temperatures estimated at the limited number of depths. When determining hourly CH<sub>4</sub> fluxes with the MDM, soil temperatures and the active layer depth are assumed to remain constant throughout the day.

### 2.1.3. Hydrological Module

[19] In this study, the methane module requires soil moisture estimates for each 1 cm soil layer within the profile and the estimated depth of the water table in wetland soils. We use an updated version of the hydrological module (HM) [Zhuang *et al.*, 2002] to provide these estimates. Module improvements include (1) the consideration of surface runoff when determining infiltration rates from rain throughfall and snowmelt, (2) the inclusion of the effects of temperature and vapor pressure deficit on canopy water conductance when estimating evapotranspiration based on *Waring and Running* [1998] and *Thornton* [2000], (3) a more detailed representation of water storage and fluxes within the soil profile of upland soils based on the use of the Richards equation in the unsaturated zone [Hillel, 1980], and (4) the development of daily estimates of soil moistures and water fluxes within the soil profile instead of monthly estimates. As the original version of the HM is designed to simulate water dynamics only in upland soils, algorithms have also been added to simulate water dynamics in wetland soils.

[20] For wetlands, the soil profile is divided into two zones based on the water table depth: (1) an oxygenated, unsaturated zone and (2) an anoxic, saturated zone. The soil water content and the water table depth in these wetland soils are determined using a water-balance approach that considers precipitation, runoff, drainage, snowmelt, snow sublimation, and evapotranspiration. We assume that wetland soils are always saturated below 30 cm, which represents the maximum water table depth [Granberg *et al.*, 1999]. Daily soil moisture at each 1 cm depth above the water table is modeled with a quadratic function and increases from the soil surface to the position of the water table [Granberg *et al.*, 1999]. Infiltration, runoff, snowmelt, snow sublimation, and evapotranspiration are simulated in wetlands using the same algorithms as for uplands. Drainage from wetlands is assumed to vary with soil texture, but does not exceed 20 mm d<sup>-1</sup>. The modifications to the HM and the new wetland algorithms are described in more detail in Appendix D. When estimating hourly CH<sub>4</sub> fluxes with the MDM, soil moistures and the water table depth are assumed to remain constant throughout the day.

### 2.1.4. Carbon/Nitrogen Dynamics Module

[21] We assume that the production of root exudates during the growing season enhances methanogenesis by

increasing the availability of organic carbon substrate. To capture the effect of the spatial and temporal variations in root exudates on methanogenesis, we use monthly net primary productivity (NPP) estimates from the carbon/nitrogen dynamics module (CNDM) of the Terrestrial Ecosystem Model (TEM) [Zhuang *et al.*, 2003]. The NPP estimates are used as an indicator for the seasonal and interannual variations in methanogenic substrate as follows:

$$f(S_{OM}(z, t)) = \left(1 + \frac{NPP(mon)}{NPP_{MAX}}\right) f(C_{DIS}(z)), \quad (5)$$

where NPP(mon) is monthly net primary productivity (g C m<sup>-2</sup> month<sup>-1</sup>); NPP<sub>MAX</sub> represents the maximum monthly NPP expected for a particular vegetation type (Table 1);  $f(C_{DIS}(z))$  is a multiplier that describes the relative availability of organic carbon substrate at depth  $z$  (centimeters) in the soil profile; and  $t$  represents time (hour). While organic substrates associated with fine root mortality are assumed to be available throughout the year, the ratio of NPP(mon) to NPP<sub>MAX</sub> is used to represent the additional availability of root exudates during the growing season (i.e., NPP greater than 0.0). Hence the first term on the right-hand side of equation (5) is assumed to equal 1.0 during the dormant season. We assume the simulated monthly NPP remains constant throughout the month. As a result of root mortality, we assume that  $f(C_{DIS}(z))$  is equal to 1.0 throughout the rooting zone (i.e.,  $z$  is above the rooting depth). If  $z$  is below the rooting depth, the effect of  $f(C_{DIS}(z))$  is assumed to decrease exponentially with depth [Walter and Heimann, 2000] as follows:

$$f(C_{DIS}(z)) = e^{\frac{-(z-R_D)}{10.0}}, \quad (6)$$

where  $R_D$  is the rooting depth (centimeters) as determined by the soil texture and the vegetation type [Vörösmarty *et al.*, 1989] found at the site.

## 2.2. Methane Dynamics Module Parameterization

[22] We parameterize the methane dynamics module (MDM) using measurements of CH<sub>4</sub> fluxes and key soil and climate factors made at six field sites in North America between 53°N and 68.5°N (Table 2). For wetland ecosystems, we parameterize the MDM by minimizing the differences between observed fluxes and simulated fluxes at the Toolik-D, Toolik-W, and SSA-FEN field sites. For each site, we start the parameterization procedure with an initial set of parameter values determined by a review of the literature. Each individual parameter has been adjusted to be within a range of values provided from the literature review until the root-mean-square error (RMSE) between the daily simulated and observed CH<sub>4</sub> fluxes is minimized. This procedure is conducted sequentially for all parameters with the result that RMSE for the Toolik-D, Toolik-W, and SSA-FEN parameterizations are 20, 52, and 42 mg CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>, respectively.

[23] Unlike the wetland sites, we do not have a daily time series of CH<sub>4</sub> flux data for the other three upland sites (B-F, Tundra-NS, and Tundra-UI). Therefore we parameterize the MDM for upland ecosystems such that the difference

**Table 2.** Site Descriptions Including Soil Characteristics, Driving Data, and Observational Data Used to Parameterize and Test the Model

| Site Name   | Location<br>(Lon./Lat.) | Elevation,<br>m | Vegetation   | Soil and Climate<br>Characteristics  | Driving Climate Data  | Observed Data   | Sources and Comments  |
|---|-------------------------|-----------------|--|--|---|---|---|
| <i>Calibration Sites for Tundra Ecosystems</i>        |                         |                 |  |  |   |   |   |
| Moist tundra on Unalaska Island (Tundra-UI)           | 167°W/53°N              | -               | wet tundra   | air temperatures ranged from 5 to 8°C; soil pH is 5.7  | climate data from Shenyua USAF (lat. 52°43'N, lon. 174°06'W) <sup>a</sup>   | static chamber measured CH <sub>4</sub> uptake  | Whalen and Reeburgh [1990a]; <a href="http://www.wrcc.dri.edu">http://www.wrcc.dri.edu</a>  |
| Tundra at Toolik Station of Alaska (Toolik-D)         | 149° 36'W /68°38'N      | 760             | tussock tundra                                       | continuous permafrost, short cool summers, long cold winters; the soils unevenly covered with an organic mat 0–30 cm thick, underlain by a silty mineral soil. The maximum depth of thaw is 30–50 cm, soil pH is 5.0             | air temperatures and precipitation (1991–1996) from the site, winter precipitation use 30-year average values of daily data at arctic village, Alaska station (lat. 68°08'N, lon. 145°32'W) | soil temperatures at depths 10, 20, and 50 cm, CH <sub>4</sub> fluxes of 1992 and 1993  | see <a href="http://ecosystems.mbl.edu/ARC">http://ecosystems.mbl.edu/ARC</a> and <a href="http://www.wrcc.dri.edu">http://www.wrcc.dri.edu</a>                           |
| Tundra at Toolik Station of Alaska (Toolik-W)         | same as above           | 760             | wet tussock tundra                                   | vegetation is wet tundra, soil pH is 5.0   | same as above   | soil temperatures at depths 3, 5, 7, 9, and 11 cm, CH <sub>4</sub> fluxes from 1994 and 1995 at the ARCSS-LAILI site  | King <i>et al.</i> [1998]; also see <a href="http://www-nsidc.colorado.edu/data/arcss013.html">http://www-nsidc.colorado.edu/data/arcss013.html</a>                       |
| Tundra at north slope of Alaska (Tundra-NS)           | -                       | -               | sedge, moss tussock tundra                           | predominately saturated soils, continuous permafrost, thick peats  | climate data from NOAA records for Fairbanks International Airport from 1986 to 1991 <sup>b</sup>   | static chamber CH <sub>4</sub> uptake   | King <i>et al.</i> [1989]   |
| <i>Calibration Sites for Boreal Forest Ecosystems</i> |                         |                 |  |  |   |   |   |
| Boreal forest at Bonanza Creek of Alaska (B-F)        | 148°15'W/64°41'N        | 133             | black spruce, feather moss                           | Pergelic Cryaquepts, parent material is Alluvium, forest floor depth is 20 cm, intermittent permafrost. The active layer thickness is highly variable. Some years the frozen layer persists at a depth of 140 cm. Soil pH is 5.4 | climate data from NOAA records for Fairbanks International Airport, 6 km south of study site, from 1986 to 1991   | CH <sub>4</sub> fluxes from late May to September of 1990   | Whalen <i>et al.</i> [1991]; see <a href="http://www.lter.uaf.edu/">http://www.lter.uaf.edu/</a>  |
| Fen at southern study area of BOREAS (SSA-FEN)        | 105°57'W/53°57'N        | 524.7           | complex fen with buckbean, sedges, birch, and willow | depth of peat is 1–3 m; high temperature (>20°C) and vapor pressure deficit (>1.5 kPa); soil pH is 7.1   | daily temperature and precipitation are from the Canadian AES station-Nipawin station from 1994–1996; vapor pressure from the CRU data for the grid cell <sup>c</sup>                       | soil temperatures at 10 and 20 cm depth, daily evapo-transpiration and eddy covariance measurements of CH <sub>4</sub> fluxes for May to October of 1994 and 1995 | Sellers <i>et al.</i> [1997]; Newcomer <i>et al.</i> [2000]; Stuyker <i>et al.</i> [1996, 1997]   |
| Tundra at Fairbanks of Alaska (Tundra-F)              | 147°51'W/64°52'N        | 158.5           | tussock tundra, dominated by Eriophorum              | poorly drained soil, underlain by permafrost; typical interior Alaska climate, little standing water, soils are saturated during freeze-up; soil pH is 5.4   | climate data from NOAA records for Fairbanks International Airport, 6 km south of study site, from 1987 to 1990   | three sites of CH <sub>4</sub> emissions observed using chamber techniques from 1987 to 1990  | see Whalen and Reeburgh [1992]; Ojima <i>et al.</i> [2000]; <a href="http://www.nrel.colostate.edu/projects/tragnet/">http://www.nrel.colostate.edu/projects/tragnet/</a> |

Table 2. (continued)

| Site Name   | Location<br>(Lon./Lat.) | Elevation,<br>m | Vegetation  | Soil and Climate<br>Characteristics  | Driving Climate Data  | Observed Data  | Sources and Comments   |
|---|-------------------------|-----------------|---|--|---|--|--|
| Fen at northern<br>study area of<br>BOREAS<br>(NSA-FEN) | 98°25'W/55°55'N         | 218             | fen complex including<br>sedge ( <i>Carex</i> spp.),<br>moss, moat,<br>and shrubs | shrub-dominated hummock-hollow;<br>permafrost peat plateau; soil pH<br>ranges from 3.8 to 7.2. | daily temperature and precipitation<br>from Manitoba station of<br>Canadian AES from 1994 to<br>1996; vapor pressure data from<br>CRU data sets for the grid cell | soil temperatures at depths<br>5, 10, 20, 50, and 100 cm;<br>water table depth (1994)<br>and chamber measurements<br>of CH <sub>4</sub> fluxes of<br>May–September 1994 and<br>June–October 1996 | see Newcomer <i>et al.</i><br>[2000]; Bubier <i>et al.</i><br>[1995, 2000] |

<sup>a</sup>Shemya United States Air Force (USAF) Base station.<sup>b</sup>National Oceanic and Atmospheric Administration (NOAA).<sup>c</sup>Canadian Atmospheric Environment Service (AES); Climate Research Unit (CRU) of the University of East Anglia in the United Kingdom (Mitchell *et al.*, submitted manuscript, 2004).

between the simulated and observed maximum daily CH<sub>4</sub> consumption rate is minimized at these sites. Specifically, we alter the parameters of the methane module until the simulated CH<sub>4</sub> consumption by soils reaches the maximum consumption rate of 0.95, 1.2, and 2.7 mg CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup> at the B-F, Tundra-NS, and Tundra-UI sites, respectively. Because the meteorological observations of some sites are not available to us, we use climatic data from other sources (see Table 2), and it is possible that this may lead to biases in the parameterization. In addition, our approach of adjusting a single parameter at a time may lead to biases in parameterizations. The ecosystem-specific parameters for the MDM based on these site calibrations are documented in Table 1.

### 2.3. Model Testing at the Site Level

[24] To test the model and validate our parameterizations, we conduct simulations for a boreal forested wetland site (NSA-FEN) in Canada and a tundra site (Tundra-F) at Fairbanks, Alaska (Table 2), which are not used during our parameterization process. To evaluate model performance, we compare the simulated daily CH<sub>4</sub> fluxes to observed fluxes at these sites. The SSA-FEN parameterization is used for the NSA-FEN site simulations, and the Toolik-W parameterization is used for the Tundra-F site simulations.

### 2.4. Regional Simulations Using Geographically Explicit Data

[25] To make spatially and temporally explicit estimates of CH<sub>4</sub> emissions and consumption in the northern high latitudes (north of 45°N) with our new version of TEM, we use spatially explicit data of climate, land cover, soils, daily climate, and monthly leaf area index (LAI) from a variety of sources. The model is applied at the spatial resolution of 0.5° latitude × 0.5° longitude and at a daily time step for the period 1900 through 2000.

[26] The static data sets include potential vegetation [Melillo *et al.*, 1993], soil texture [Zhuang *et al.*, 2003], the distribution of wet soils and the fractional inundation of wetlands [Matthews and Fung, 1987], and soil-water pH [Carter and Scholes, 2000]. Similar to earlier versions of TEM, the vegetation and soil texture data sets are used to assign vegetation-specific and texture-specific parameters to a grid cell. The remaining spatially explicit data sets are needed to provide inputs into the new MDM. The wet soils and the fractional inundation of wetlands data sets are used to derive the proportions of wetlands and uplands within each 0.5° × 0.5° grid cell. The soil-water pH data set is used to estimate methanogenesis across the study region.

[27] The daily climate data sets are derived from the historical monthly air temperature, precipitation, vapor pressure, and cloudiness data sets (T. D. Mitchell *et al.*, A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: The observed record (1901–2000) and 16 scenarios (2001–2100), submitted to *Journal of Climatology*, 2004) (hereinafter referred to as Mitchell *et al.*, submitted manuscript, 2004) of the Climatic Research Unit (CRU) of the University of East Anglia in the United Kingdom. We linearly interpolate the monthly air temperature and vapor pressure to daily data using three



consecutive month's data. To determine a current month's daily air temperatures, for example, we assume that (1) the value of day 15 is equal to the current month's mean air temperature, (2) the value of the first day is equal to the average monthly air temperature of the current month and the previous month, and (3) the value of last day is equal to the average monthly air temperature of the current and the next month. The temperatures for the other days are linearly interpolated using values of the first, fifteenth, and last days. To convert monthly precipitation into daily rainfall, we use the statistical algorithm of *Li and Frolking* [1992] and *Liu* [1996]. The algorithm converts the monthly precipitation into a number of rainfall events of different duration and intensity based on air temperature and the correlation of monthly precipitation with the frequency of heavy, intermediate, and small rainfall events.

[28] In the HM, monthly LAI is used to estimate transpiration (Appendix D) [*Zhuang et al.*, 2002]. We use monthly LAI data sets derived from satellite imagery for the period 1982 to 1999 [*Myneni et al.*, 1997, 2001] to prescribe LAI for each  $0.5^\circ$  latitude  $\times$   $0.5^\circ$  longitude grid cell. From 1900 to 1981, we use the LAI of 1982 to represent LAI during this period. We also use the LAI of 1999 to represent LAI during 2000. During our simulations, LAI is assumed to remain constant within a month.

[29] To develop regional estimates of  $\text{CH}_4$  exchange from 1900 to 2000, we simulate the methane dynamics and

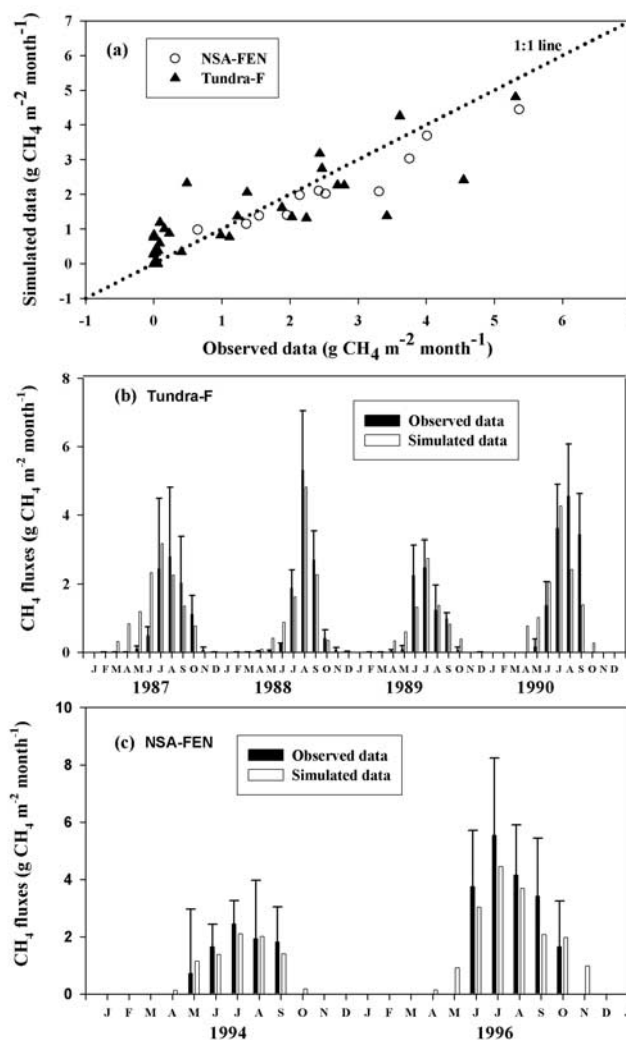
estimate daily  $\text{CH}_4$  fluxes from both wetland and upland ecosystems in each  $0.5^\circ$  latitude  $\times$   $0.5^\circ$  longitude grid cell. These ecosystem-specific  $\text{CH}_4$  flux estimates are then area-weighted for each grid cell, as defined by the fractional inundation data set of *Matthews and Fung* [1987], to determine the  $\text{CH}_4$  fluxes from each  $0.5^\circ$  latitude  $\times$   $0.5^\circ$  longitude grid cell.

### 3. Results and Discussion

#### 3.1. Site-Specific Testing

[30] At the test site Tundra-F, the simulation captures the interannual and seasonal variations of the net  $\text{CH}_4$  emissions. The simulated annual emissions are 12.2, 10.4, 7.6, and 12.1  $\text{g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$  for 1987, 1988, 1989, and 1990, respectively, compared to observed emissions of  $8.05 \pm 2.5$ ,  $11.38 \pm 2.88$ ,  $8.11 \pm 1.80$ , and  $13.64 \pm 1.20$   $\text{g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$  for the same years [see *Whalen and Reeburgh*, 1992]. The geometric mean regression statistics [*Sokal and Rohlf*, 1981] shows a significant ( $P < 0.01$ ;  $N = 48$  months) relationship between the simulated and observed monthly emissions with  $R^2 = 0.77$ , slope =  $0.86 \pm 0.06$ , and intercept =  $0.17 \pm 0.10$   $\text{g CH}_4 \text{ m}^{-2} \text{ month}^{-1}$  (Figure 2a). Overall, the

**Figure 2.** Comparisons between simulated and observed  $\text{CH}_4$  emissions at the test sites including (a) a scatterplot of observed versus simulated monthly  $\text{CH}_4$  emissions for the two sites; (b) a time series of the observed and simulated monthly  $\text{CH}_4$  emissions at the Tundra-F site during the period 1987 to 1990; and (c) a time series of the simulated and observed monthly  $\text{CH}_4$  emissions at the NSA-FEN test site during 1994 and 1996. The test sites are described in Table 2. The dashed line in Figure 2a indicates the 1:1 line for the regressions. For the NSA-FEN site, the statistics are significant ( $P < 0.01$ ,  $N = 10$  months) with  $R^2 = 0.90$ , slope =  $0.70 \pm 0.07$ , and intercept =  $0.35 \pm 0.23$   $\text{g CH}_4 \text{ m}^{-2} \text{ month}^{-1}$ . Similarly, for the Tundra-F site, the statistics are significant ( $P < 0.01$ ,  $N = 48$  months) with  $R^2 = 0.77$ , slope =  $0.86 \pm 0.06$ , and intercept =  $0.17 \pm 0.10$   $\text{g CH}_4 \text{ m}^{-2} \text{ month}^{-1}$ . Error bars in Figure 2b indicate the standard deviations for the mean monthly observations from three tussock tundra subsites, T1, T2, and T3; see *Whalen and Reeburgh* [1992] for more details. The observed monthly data in Figure 2b is aggregated from available daily data from February to December of 1987, January to December of 1988 and 1989, and from May to September of 1990. The observed daily data in Figure 2c are averaged from  $\text{CH}_4$  chamber flux measurements at six subsites in 1994 and four subsites in 1996. These subsites represent the range of plant communities, water chemistry, and peatland types found in northern peatlands, including bog, rich fen, poor fen, and collapse scars. The observed monthly data in Figure 2c is aggregated from available daily data from May to September of 1994 and from June to October of 1996. Error bars in Figure 2c indicate the standard deviations for the mean monthly observations from these subsites.





simulations tend to have higher emissions compared to the observations during the spring of each year (Figure 2b). This discrepancy occurs because the model assumes that the winter snowpack insulates the soil from the frigid air temperatures during the winter such that soil temperatures remain relatively high. The higher soil temperatures lead to an earlier spring thaw, which in turn leads to earlier CH<sub>4</sub> production at the site. In 1990, the model underestimates the emissions in August and September. This is primarily because the simulated water table ranges from 27 to 28 cm, which is deeper than the measured maximum depth of 23 cm. The deeper water table leads to less CH<sub>4</sub> production and emissions.

[31] Similarly, at the NSA-FEN test site, the model is able to capture the interannual and seasonal dynamics of net CH<sub>4</sub> emissions in 1994 and 1996. A geometric mean regression between the monthly simulated and observed net emissions is significant ( $P < 0.01$ ;  $N = 10$  months) with  $R^2 = 0.90$ , slope =  $0.73 \pm 0.07$ , and intercept =  $0.35 \pm 0.23$  g CH<sub>4</sub> m<sup>-2</sup> month<sup>-1</sup> (Figure 2a). The model slightly underestimates the emissions from June to September in 1996 (Figure 2c). Our analyses suggest that the lower emissions in our simulation are primarily due to the lower soil temperatures resulting from the low soil thermal conductivity prescribed for the model at this site. The deviation is also partially due to the climate data used to drive the model. Owing to the lack of in situ meteorological data at the site, data from the Thompson station of the Canadian Atmospheric Environment Service (AES) has been used to drive the model for this analysis.

### 3.2. Contemporary Regional and Subregional Fluxes

[32] Overall, our simulations estimate that the Pan-Arctic region has been a mean source of about 51 Tg CH<sub>4</sub> yr<sup>-1</sup> during the 1990s. This estimate is in the same range as a number of other recent estimates that have been made using a variety of approaches (Table 3). Differences between our estimates and those of other studies may be a result of using different geographical boundaries or assuming different importance of various ecosystems in contributing methane to the atmosphere. For example, *Walter et al.* [2001b] considered areas north of 30°N in developing their regional estimates rather than the 45°N boundary used in this study. Several studies considered only tundra, boreal forests, or wetlands when developing their regional estimates. In our study, we estimate that the source strength varies over the Pan-Arctic and that large regions have actually been small net sinks of atmospheric CH<sub>4</sub> (Figure 3).

[33] In our simulations, wetlands act as a net source of CH<sub>4</sub>, whereas upland areas act as a net sink. We estimate that wetlands across the Pan-Arctic emitted about 57 Tg CH<sub>4</sub> yr<sup>-1</sup> during the 1990s. Wetlands within boreal forests have the highest rates of emissions (23 g CH<sub>4</sub> m<sup>-2</sup> yr<sup>-1</sup>), but the large areas of wetlands within wet tundra cause these ecosystems to be the largest contributor of atmospheric CH<sub>4</sub>.

[34] In addition to the estimates of net CH<sub>4</sub> emissions from wetlands, our simulations estimate that soil microbes in upland areas have consumed about 6 Tg CH<sub>4</sub> yr<sup>-1</sup> across the Pan-Arctic during the 1990s. This estimate is higher in comparison to most other studies of methane consumption (Table 3), which estimate the consumption rate to be

**Table 3.** Emissions, Consumption, and Net Emissions of Methane From Ecosystem Soils Across the Pan-Arctic Region During the 1990s

|                                    | Emissions,<br>Tg CH <sub>4</sub><br>yr <sup>-1</sup> | Consumption,<br>Tg CH <sub>4</sub><br>yr <sup>-1</sup> | Net Emissions,<br>Tg CH <sub>4</sub><br>yr <sup>-1</sup> |
|------------------------------------|--|--|--|
| TEM                                | 57.3   | 6.3  | 51.0   |
| Other studies                      |  |  |  |
| <i>Whalen and Reeburgh</i> [1992]  | 42 ± 26 <sup>a</sup>                                 |  |  |
| <i>Whalen and Reeburgh</i> [1990a] | 53 <sup>b</sup>                                      |  |  |
| <i>Sebacher et al.</i> [1986]      | 45–106 <sup>c</sup>                                  |  |  |
| <i>Bartlett and Harriss</i> [1993] | 38 <sup>d</sup>                                      |  |  |
| <i>Matthews and Fung</i> [1987]    | 62 <sup>e</sup>                                      |  |  |
| <i>Crill et al.</i> [1988]         | 72 <sup>f</sup>                                      |  |  |
| <i>Walter et al.</i> [2001a]       | 65 <sup>g</sup>                                      |  |  |
| <i>Cao et al.</i> [1998]           | 31 <sup>h</sup>                                      |  |  |
| <i>Harriss et al.</i> [1993]       | 35 <sup>i</sup>                                      |  |  |
| <i>Liu</i> [1996]                  | 47 <sup>j</sup>                                      |  |  |
| <i>Born et al.</i> [1990]          |  | 1–15 <sup>k</sup>                                      |  |
| <i>Whalen et al.</i> [1991]        |  | 0–0.8 <sup>l</sup>                                     |  |
| <i>Steudler et al.</i> [1989]      |  | 0.3–5.1 <sup>m</sup>                                   |  |
| <i>Ridgwell et al.</i> [1999]      |  | 5.5 <sup>n</sup>                                       |  |
| <i>Potter et al.</i> [1996]        |  | 2.4 <sup>o</sup>                                       |  |
| <i>Chen</i> [2004]                 |  |  | 42–45 <sup>p</sup>                                       |

<sup>a</sup>Estimates for Arctic wet meadow and tussock and shrub tundra.

<sup>b</sup>Estimates for global tundra and taiga ecosystems.

<sup>c</sup>Estimates for Arctic and boreal wetlands.

<sup>d</sup>Estimates for northern wetlands north of 45°N.

<sup>e</sup>Estimates for forested and non-forested bogs between 50°N and 70°N.

<sup>f</sup>Estimates for undrained peatlands north of 40°N.

<sup>g</sup>Estimates for wetlands north of 30°N.

<sup>h</sup>Estimates for natural wetlands north of 40°N.

<sup>i</sup>Estimates for northern tundra and taiga.

<sup>j</sup>Estimates for natural wetlands between 40°N and 80°N.

<sup>k</sup>Estimates for boreal forests.

<sup>l</sup>Estimates for upland and floodplain taiga.

<sup>m</sup>Estimates for boreal forests.

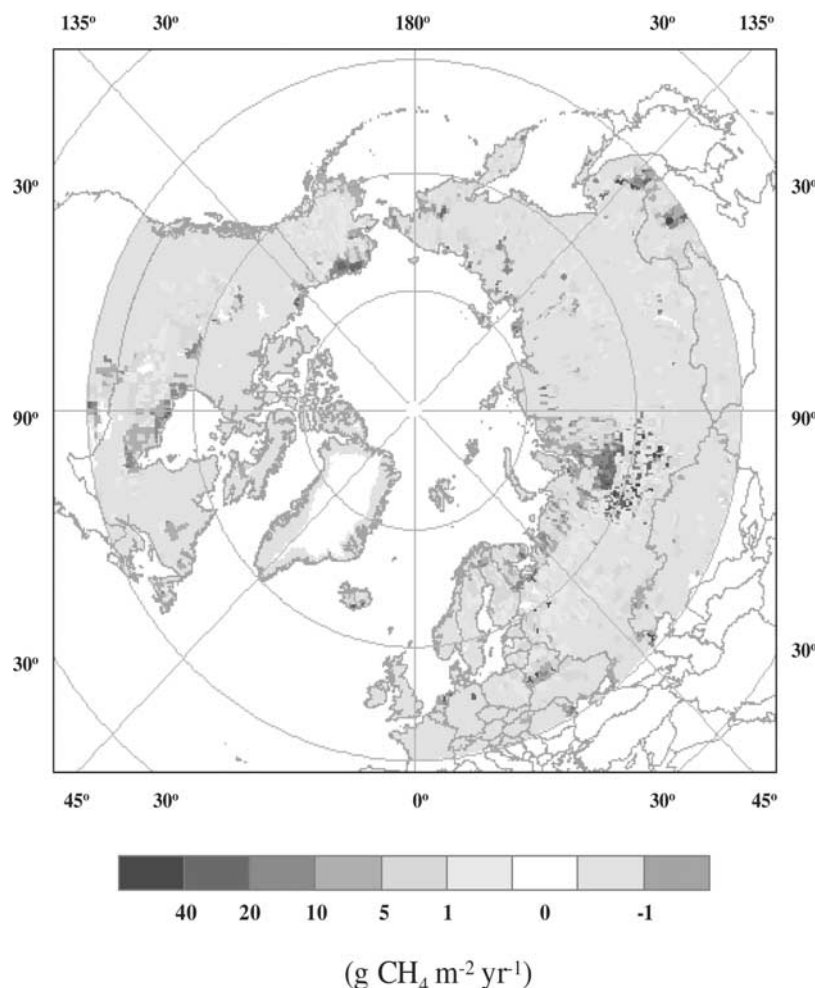
<sup>n</sup>Estimates for tundra and boreal forests.

<sup>o</sup>Estimates for tundra and boreal forests.

<sup>p</sup>Estimates based on inverse modeling for the Northern Hemisphere.

between 0 and 5.5 Tg CH<sub>4</sub> yr<sup>-1</sup>. An exception is the *Born et al.* [1990] study, which suggested a consumption rate of up to 15 Tg CH<sub>4</sub> yr<sup>-1</sup>. In developing our estimates of CH<sub>4</sub> emissions, we do not consider the potential effects of moisture hindrance on methane diffusion through unsaturated soil. As a result, our model may overestimate actual consumption rates. Upland areas within wet tundra have the highest consumption rates (0.27 g CH<sub>4</sub> m<sup>-2</sup> yr<sup>-1</sup>) because the simulated soil moisture in wet tundra is closer to the optimum soil moisture for methanotrophy than that simulated for upland boreal forests.

[35] The simulated CH<sub>4</sub> emissions and consumption vary across the region as a result of the distribution of wetlands as well as the spatial variability in climate (Figure 3). For the 1990s, our simulations estimate that terrestrial ecosystems within Russia, Canada, and Alaska are the major sources of CH<sub>4</sub> emissions in the Pan-Arctic, which are contributing 64%, 11%, and 7%, respectively, of the total net CH<sub>4</sub> emissions per year (51.0 Tg CH<sub>4</sub> yr<sup>-1</sup>, Table 4). Within Russia, we estimate that the net CH<sub>4</sub> emissions from the West Siberia wetlands are 21g CH<sub>4</sub> m<sup>-2</sup> yr<sup>-1</sup>, for a total of 12 Tg CH<sub>4</sub> yr<sup>-1</sup>, which is close to the high end of the mean estimates of 0.3–14 Tg CH<sub>4</sub> yr<sup>-1</sup> by *Smith et al.* [2004], but lower than the mean estimate of 26 g CH<sub>4</sub>



**Figure 3.** Simulated net CH<sub>4</sub> emissions and consumption in the Pan-Arctic region during the 1990s. Positive values indicate the net CH<sub>4</sub> release to the atmosphere, and negative values indicate the CH<sub>4</sub> uptake from the atmosphere. See color version of this figure at back of this issue.

$\text{m}^{-2} \text{yr}^{-1}$  by Friborg *et al.* [2003] for this region. Consumption of methane is more evenly distributed across the Pan-Arctic. The soils of Russia, Canada, and Alaska account for 38%, 25%, and 5%, respectively, of the total CH<sub>4</sub> consumed per year ( $6.3 \text{ Tg CH}_4 \text{ yr}^{-1}$ , Table 4) in this region.

[36] Our simulations indicate that 60% of the net CH<sub>4</sub> emissions come from the latitude band of  $45^\circ\text{N}$ – $60^\circ\text{N}$  as compared to 40% of total emissions from the region of  $60^\circ\text{N}$ – $75^\circ\text{N}$ , Table 5). This pattern is probably due to the larger areas of wetlands in the southern Pan-Arctic compared to the middle Pan-Arctic. However, wetlands represent a

larger proportion of the land area in the middle Pan-Arctic than the southern Pan-Arctic such that the mean net emissions per square meter are actually higher in the middle Pan-Arctic. The consumption in the southern Pan-Arctic is also 2 times larger than in the middle Pan-Arctic, which is primarily due to the larger forest area in the southern Pan-Arctic.

**Table 4.** Regional Variation in Emissions, Consumption, and Net Emissions of Methane During the 1990s

|   | Russia | Canada | Alaska | Pan Arctic |
|---|--------|--------|--------|------------|
| Emissions, $\text{Tg CH}_4 \text{ yr}^{-1}$     | 35.1   | 7.1    | 3.8    | 57.3       |
| Consumption, $\text{Tg CH}_4 \text{ yr}^{-1}$   | −2.3   | −1.5   | −0.3   | −6.3       |
| Net emissions, $\text{Tg CH}_4 \text{ yr}^{-1}$ | 32.8   | 5.6    | 3.5    | 51.0       |
| Land area, $10^{10} \text{ m}^2$                | 687.4  | 370.2  | 65.2   | 3826       |

**Table 5.** Latitudinal Variations in Emissions, Consumption, and Net Emissions of Methane During the 1990s

|  | Northern<br>Pan-Arctic<br>( $75^\circ\text{N}$ – $90^\circ\text{N}$ ) | Middle<br>Pan-Arctic<br>( $60^\circ\text{N}$ – $75^\circ\text{N}$ ) | Southern<br>Pan-Arctic<br>( $45^\circ\text{N}$ – $60^\circ\text{N}$ ) | Pan-Arctic<br>( $45^\circ\text{N}$ – $90^\circ\text{N}$ ) |
|--|---|---|---|---|
| Emissions,<br>$\text{Tg CH}_4 \text{ yr}^{-1}$     | 0.2   | 23.0  | 34.0  | 57.3  |
| Consumption,<br>$\text{Tg CH}_4 \text{ yr}^{-1}$   | −0.2  | −2.0  | −4.0  | −6.3  |
| Net emissions,<br>$\text{Tg CH}_4 \text{ yr}^{-1}$ | 0.0   | 21.0  | 30.0  | 51.0  |
| Land area, $10^{10} \text{ m}^2$                   | 58.7  | 1473.3  | 2294.6  | 3826  |

**Table 6.** Decadal Variations in Climate, Net Primary Productivity (NPP), and CH<sub>4</sub> Fluxes for the Past Century in the Pan-Arctic Region

|  | 1900s | 1910s | 1920s | 1930s | 1940s | 1950s | 1960s | 1970s | 1980s | 1990s |
|--|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| CH <sub>4</sub> emissions, Tg CH <sub>4</sub> yr <sup>-1</sup>     | 47.8  | 48.0  | 51.5  | 51.7  | 50.7  | 53.4  | 50.7  | 50.7  | 53.8  | 57.3  |
| CH <sub>4</sub> consumption, Tg CH <sub>4</sub> yr <sup>-1</sup>   | -6.0  | -6.1  | -6.1  | -6.2  | -6.2  | -6.2  | -6.1  | -6.2  | -6.2  | -6.3  |
| Net CH <sub>4</sub> emissions, Tg CH <sub>4</sub> yr <sup>-1</sup> | 41.8  | 41.9  | 45.4  | 45.5  | 44.5  | 47.2  | 44.6  | 44.5  | 47.6  | 51.0  |
| Mean annual air temperatures, °C                                   | -4.0  | -4.0  | -3.7  | -3.5  | -3.5  | -3.7  | -3.7  | -3.7  | -3.3  | -2.9  |
| Mean annual precipitation, mm                                      | 471   | 474   | 473   | 478   | 484   | 494   | 505   | 503   | 507   | 505   |
| Mean annual soil temperatures, °C                                  | -1.2  | -1.2  | -1.0  | -0.9  | -0.9  | -1.0  | -1.0  | -1.0  | -0.7  | -0.5  |
| Mean annual water table depths, mm                                 | 198.6 | 198.8 | 199.5 | 200.5 | 200.5 | 199.6 | 199.6 | 200.0 | 201.5 | 202.9 |
| NPP, Pg C yr <sup>-1</sup>   | 8.3   | 8.4   | 8.3   | 8.6   | 8.7   | 8.7   | 8.7   | 8.7   | 9.0   | 9.1   |

### 3.3. Twentieth Century Trends

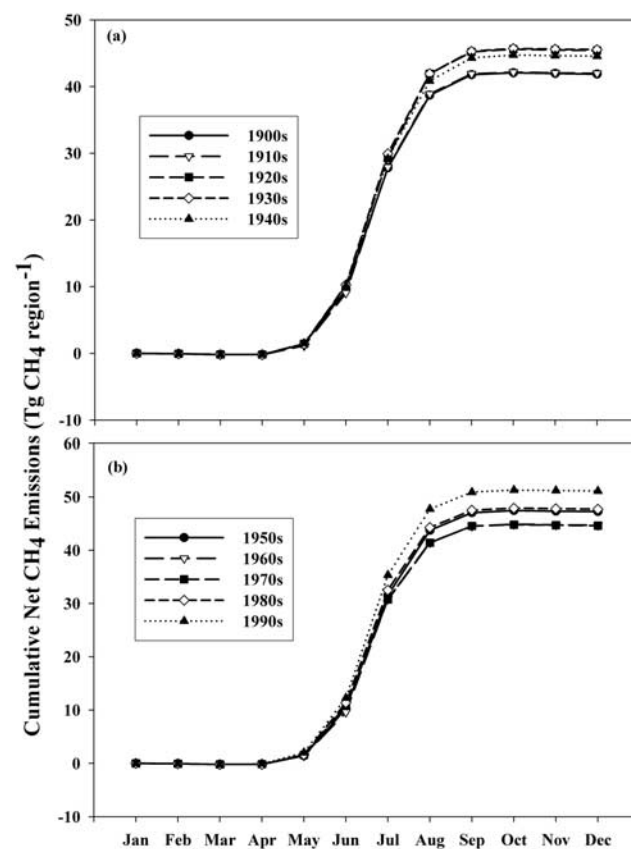
[37] During the past century, our simulations estimate that net CH<sub>4</sub> emissions have increased at a rate of 0.08 Tg CH<sub>4</sub> yr<sup>-1</sup> estimated as the slope of the linear regression between the annual net emissions and year from 1900 to 2000. For the 1980s, however, the model simulates a larger increasing trend in CH<sub>4</sub> emissions ( $\sim 1.0$  Tg CH<sub>4</sub> yr<sup>-1</sup>, estimated as the slope of the linear regression between the annual net emissions and year from 1980 to 1989). The increased trend of net emissions during this period is consistent with the increased trend ( $11.6 \pm 0.2$  ppbv yr<sup>-1</sup>) of the observed atmospheric CH<sub>4</sub> concentrations during 1983–1991 in the Northern Hemisphere [Dlugokencky *et al.*, 1994].

[38] While methane consumption rates remain fairly constant throughout the study period, net CH<sub>4</sub> emissions vary from decade to decade (Table 6) with relatively large emissions in the 1920s–1930s, 1950s, and 1980s–1990s. The decadal net CH<sub>4</sub> emission rates are correlated with decadal variations in climate and its derived variables, namely, soil temperature, water table depth, and NPP. Our analyses indicate that net CH<sub>4</sub> emissions are more significantly correlated with air temperature ( $R^2 = 0.81$ ;  $P < 0.01$ ,  $N = 10$  decades) than precipitation ( $R^2 = 0.40$ ;  $P < 0.01$ ;  $N = 10$  decades). The correlations between decadal net CH<sub>4</sub> emissions and water table depth, soil temperature, and NPP are significantly ( $P < 0.01$ ) high, with  $R^2$  values of 0.65, 0.82, and 0.65, respectively. These analyses suggest that changes in climate and its influence on ecosystem production and the soil environment could significantly influence the dynamics of CH<sub>4</sub> emissions.

[39] Decadal changes of simulated monthly emissions from the 1900s to 1990s also show an increasing trend in the magnitude of net CH<sub>4</sub> emissions during the growing season (May through September; see Figure 4) when root exudates provide additional carbon for methanogenesis. As shown in Table 6, NPP has increased over the period. The enhanced NPP increased the input of root exudates to enhance methanogenesis and CH<sub>4</sub> emissions over this time period. Our simulations show that the peak emissions occurred in July, which is consistent with the results of recent inverse modeling studies [Houweling *et al.*, 2000; Chen, 2004] and other process-based modeling [Cao *et al.*, 1996]. This peak in monthly CH<sub>4</sub> emissions corresponds to the seasonal peak in NPP.

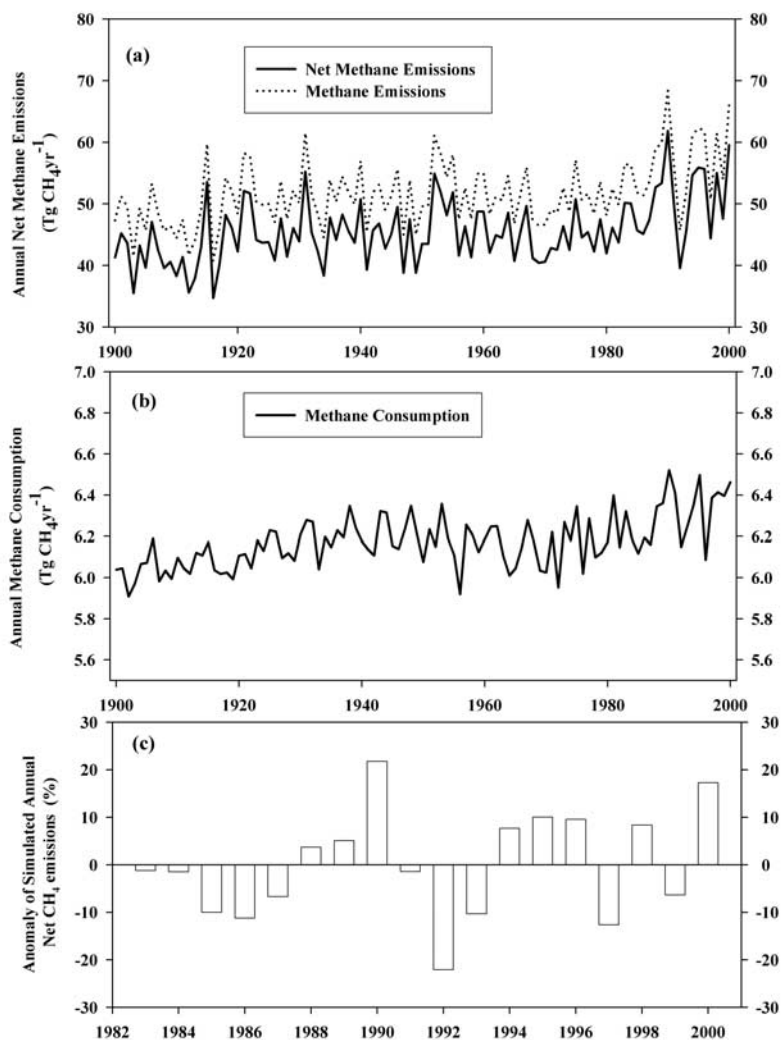
[40] Our simulations also show that large interannual variability in net CH<sub>4</sub> emissions occurred during the twentieth century (Figures 5a and 5b). For example, our simulations estimate that the net CH<sub>4</sub> emissions decrease from

50 Tg CH<sub>4</sub> yr<sup>-1</sup> in 1991 to 40 and 45 Tg CH<sub>4</sub> yr<sup>-1</sup> in 1992 and 1993, respectively, after the Mount Pinatubo eruption in 1991 (Figure 5c). This pattern of CH<sub>4</sub> emissions has also been observed in the inverse modeling study of Dlugokencky *et al.* [1994], and the modeling study of Walter *et al.* [2001b]. During 1998, there was a large positive anomaly in the global growth rate of atmospheric methane concentrations; Dlugokencky *et al.* [2001] attributed this anomaly in part to increased emissions from wetlands in northern high latitudes resulting from warm conditions in 1998 due to the strong El Niño phenomena. Our simulation results support this interpretation and indicate that the



**Figure 4.** Cumulative net CH<sub>4</sub> emissions from the Pan-Arctic region for each decade from (a) the 1900s to the 1940s and (b) the 1950s to the 1990s. Net CH<sub>4</sub> emissions of each month are averaged over each decade.





**Figure 5.** Annual methane fluxes from the Pan-Arctic region during the twentieth century including (a) annual net methane emissions, (b) annual methane consumption, and (c) anomaly of simulated net CH<sub>4</sub> emissions from 1983 to 2000. Anomalies are calculated based on the averaged net CH<sub>4</sub> emissions from 1982 to 2000.

region released 55 Tg CH<sub>4</sub> in 1998, an amount that is 8–11 Tg higher than the net CH<sub>4</sub> emissions in 1999 and 1997. However, we acknowledge that the atmospheric CH<sub>4</sub> concentrations are influenced by a variety of factors including atmospheric transport and atmospheric CH<sub>4</sub> oxidation as well as CH<sub>4</sub> emissions from other sources such as fires, landfills, industrial processing, fossil-fuel burning, and rice paddies. Thus net CH<sub>4</sub> emissions from natural wetlands can only partially explain the changes in atmospheric CH<sub>4</sub> concentrations and may at times show opposite trends. For example, our simulated net CH<sub>4</sub> emissions for the year 2000 are the second highest emissions estimated during the last decade or so in response to interannual climate variability, but the atmospheric CH<sub>4</sub> concentrations did not show a corresponding peak due to a number of different sink and source dynamics. A decrease in fire disturbances north

of 38°N [van der Werf *et al.*, 2004] and their associated emissions during 2000 may have compensated for the increases in net CH<sub>4</sub> emissions from wetlands to influence atmospheric CH<sub>4</sub> concentrations.

### 3.4. Sensitivity of Net CH<sub>4</sub> Emissions to Active Layer Depth

[41] Previous studies [Zhuang *et al.*, 2001; Romanovsky and Osterkamp, 1997] have indicated that the active layer depth may be significantly overestimated if soil thermal models do not consider the possibility of soil freezing upward from the permafrost boundary. Because the estimated active layer depth is used to determine the lower boundary of microbial activity including methanogenesis in soils of permafrost regions, the overprediction of the active layer depth will result in higher estimates of methane production and emissions. To test this hypothesis, we

increase the depth of the lower boundary by 10 cm in a sensitivity analysis. The resulting regional estimate of net CH<sub>4</sub> emissions for the Pan-Arctic region is 38% larger than that of our control simulations. This suggests that the consideration of two freezing fronts, i.e., freezing of soil upward from the permafrost boundary as well as downward from the soil surface, is important when modeling methane emissions from regions underlain with permafrost.

### 3.5. Conclusions

[42] In this study, we couple key aspects of soil thermal, hydrological, and carbon dynamics of terrestrial ecosystems with methane cycling to estimate CH<sub>4</sub> fluxes between the atmosphere and the soils of the Pan-Arctic region. By considering the ability of soils to produce methane in wetland soils and to oxidize methane in both wetland and upland soils, we have developed more comprehensive regional estimates of CH<sub>4</sub> fluxes than provided by earlier studies using either process-based models or field estimates. Our analyses suggest that CH<sub>4</sub> emissions are more sensitive to changes in climate, particularly air temperature, than consumption, such that natural ecosystems may become a larger source of atmospheric CH<sub>4</sub> with future global warming. In addition, our analyses suggest that changes in root exudates associated with climate-induced enhancements in plant productivity may also increase CH<sub>4</sub> emissions. However, reductions in the area of wetlands in the Pan-Arctic region [e.g., McGuire *et al.*, 2004] as a result of alterations of the hydrological cycle may decrease methane production and allow methane consumption by soils to become more important. Because the areal extent of wetlands has been kept constant in this study, we have not been able to evaluate the importance of this negative feedback on regional estimates of net CH<sub>4</sub> emissions.

[43] Our regional estimates of net CH<sub>4</sub> emissions from natural ecosystems are 10–20% higher than those estimated from an inverse modeling study based on spatial and temporal changes in atmospheric CH<sub>4</sub> concentrations [Chen, 2004]. To help resolve this discrepancy and to better understand the role of natural ecosystems in the global methane budget, it is desirable to couple our spatially explicit estimates of CH<sub>4</sub> fluxes to an atmospheric transport model to simulate seasonal and interannual changes in atmospheric CH<sub>4</sub> concentrations. This approach has already been taken with CO<sub>2</sub> fluxes and has proved helpful in evaluating and improving the simulation of the various aspects of the carbon cycle including terrestrial carbon sequestration [McGuire *et al.*, 2000; Dargaville *et al.*, 2002; Zhuang *et al.*, 2003].

## Appendix A: Methane Production

[44] Methane (CH<sub>4</sub>) production occurs in the saturated zone of soils. As described by equation (3) in the text, we simulate hourly CH<sub>4</sub> production rates as a function of carbon substrate availability, soil thermal conditions, soil pH, and soil redox potentials. The influence of carbon substrate availability on methanogenesis is documented in section 2.1.4. Here we describe, in more detail, the influ-

ence of soil thermal conditions, soil pH conditions, and soil redox potentials on the production rate of methane.

### A1. Effects of Soil Temperatures on Methanogenesis

[45] Many studies indicate that soil temperature influences the rate methane production [e.g., Bartlett and Harriss, 1993; Froking and Crill, 1994; Christensen *et al.*, 1995]. Here we assume the hourly methane production rate increases logarithmically with soil temperature based on work by Walter and Heimann [2000],

$$f(M_{ST}(z, t)) = P_{Q10}^{\frac{T_{SOIL}(z, t) - T_{PR}}{10}}, \quad (A1)$$

where  $P_{Q10}$  is an ecosystem-specific  $Q_{10}$  coefficient (Table 1);  $T_{SOIL}(z, t)$  is the hourly soil temperature at depth  $z$  (centimeters) and time  $t$  (hours), which is simulated by the STM module for each 1 cm depth of the soil profile; and  $T_{PR}$  is the reference temperature for methanogenesis that varies across ecosystems (Table 1).

### A2. Soil pH Effects on Methanogenesis

[46] The optimal soil-water pH for methanogenesis ranges from 6.4 to 7.8 [Minami, 1989; Wang *et al.*, 1993] with a tolerance that ranges from 5.5 to 9.0 [Skinner, 1968; Wang *et al.*, 1993]. If pH is above or below the tolerance range, methanogenesis is completely inhibited. Therefore, following Cao *et al.* [1996], we model the effect of soil pH on hourly methane production as

$$f(pH(z, t)) = \frac{(pH - pH_{MIN})(pH - pH_{MAX})}{(pH - pH_{MIN})(pH - pH_{MAX}) - (pH - pH_{OPT})^2}, \quad (A2)$$

where pH is the soil-water pH value at the site,  $pH_{MIN}$  is the minimum soil-water pH,  $pH_{MAX}$  is the maximum soil-water pH, and  $pH_{OPT}$  is the optimum soil-water pH for methane production. We assume values of 5.5, 9.0 and 7.5 for  $pH_{MIN}$ ,  $pH_{MAX}$ , and  $pH_{OPT}$ , respectively, for all soils. We also assume that the pH prescribed for a site is the same at each soil depth  $z$  (centimeters) and time  $t$  (hours).

### A3. Redox Potential Effects on Methanogenesis

[47] Redox potential ( $E_{HL}$ ) is used to model the relative availability of electron acceptors (e.g., O<sub>2</sub>, NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>-2</sup>, Fe<sup>+3</sup>, Mn<sup>+4</sup>), which suppress methanogenesis [Segers and Kengen, 1998]. On the basis of work by Zhang *et al.* [2002] and Fiedler and Sommer [2000], the effects of daily redox potential on hourly CH<sub>4</sub> production is modeled for each 1 cm depth as follows:

$$f(R_x(z, t)) = 1.0 \quad E_{HL}(z, u) \leq -200 \text{ mV}, \quad (A3a)$$

$$f(R_x(z, t)) = \alpha \times E_{HL}(z, u) - 1.0 \quad -100 \text{ mV} > E_{HL}(z, u) > -200 \text{ mV}, \quad (A3b)$$

$$f(R_x(z, t)) = 0.0 \quad E_{HL}(z, u) \geq -100 \text{ mV}, \quad (A3c)$$

where  $E_{HL}(z, u)$  is the estimated daily redox potential (mV) at soil depth  $z$  and day  $u$  and  $\alpha$  is a constant ( $-0.01 \text{ mV}^{-1}$ ).

[48] Following *Zhang et al.* [2002] and *Segers and Kengen* [1998], we model daily changes in  $E_{HL}$  as a function of the root distribution, the fraction of water filled pore space, and the water table position at the site,

$$\frac{dE_{HL}(z, u)}{du} = C_R \times (A_L - 1.0), \quad (\text{A4a})$$

if the depth  $z$  is in the saturated zone, or

$$\frac{dE_{HL}(z, u)}{du} = C_R \times (A_L + 1.0 - F_W(z)), \quad (\text{A4b})$$

if depth  $z$  is in the unsaturated zone, and

$$A_L = F_{CA} \times P_A \times R_{LD}, \quad (\text{A5})$$

where  $C_R$  is the change rate of soil redox potential under saturated conditions;  $F_W(z)$  is the fraction of water-filled pore space at depth  $z$ ;  $F_{CA}$  is the cross-sectional area of a typical fine root;  $P_A$  is a scalar for the degree of gas diffusion from root to atmosphere; and  $R_{LD}$  is the fine root length density. We assume that  $C_R$  is 100 mV,  $F_{CA}$  is  $0.0013 \text{ m}^2$ , and  $R_{LD}$  is  $10 \text{ m m}^{-3}$  [see *McClagherty et al.*, 1982] for all ecosystems. We assume  $P_A$  is 0.0 for forested ecosystems and 0.5 for other ecosystems [Zhang et al., 2002]. The HM determines  $F_W(z)$  for each 1 cm depth based on soil moisture and the porosity of the corresponding HM soil layer (i.e., moss or litter, upper organic, lower organic, upper mineral, or lower mineral, [see *Zhuang et al.*, 2002]).

## Appendix B: Methane Oxidation

[49] Methane oxidation occurs in upland soils and the unsaturated zone of wetland soils. The oxygenase pathway of methane oxidation dominates methanotrophy in terrestrial ecosystems. As described by equation (4) in the text, we model the oxidation rate as a function of soil  $\text{CH}_4$  concentration, soil temperature, soil moisture, and soil redox potential. Below, we describe in more detail the influence of each factor used in this equation.

### B1. Effects of $\text{CH}_4$ Concentrations on Methanotrophy

[50] Methane oxidation requires the methane substrate to be present in the soil. This substrate may be available in a soil layer either as a result of methanogenesis within that soil layer or by diffusion of methane into the soil layer from the surrounding soil layers or the atmosphere. Diffusion of methane through the soil profile is discussed in Appendix C. If the methane substrate is present, we assume that the effect of the  $\text{CH}_4$  concentration on oxidation follows Michaelis-Menten kinetics [see *Bender and Conrad*, 1992],

$$f(C_M(z, t)) = \frac{C_M(z, t)}{K_{\text{CH}_4} + C_M(z, t)}, \quad (\text{B1})$$

where  $C_M(z, t)$  is the hourly soil  $\text{CH}_4$  concentration ( $\mu\text{mol L}^{-1}$ ) at depth  $z$  (centimeters) and time  $t$  (hours); and  $K_{\text{CH}_4}$  is the ecosystem-specific half saturation constant for  $\text{CH}_4$  concentrations (Table 1). Typical values of  $K_{\text{CH}_4}$  constants range between 1 and  $66.2 \mu\text{mol L}^{-1}$ .

### B2. Effects of Soil Temperature on Methanotrophy

[51] Similar to methanogenesis, methanotrophy is influenced by soil temperatures. On the basis of *Walter and Heimann* [2000], we assume the hourly oxidation rate increases logarithmically with soil temperature,

$$f(T_{\text{SOIL}}(z, t)) = O_{Q10}^{\frac{T_{\text{SOIL}}(z, t) - T_{\text{OR}}}{10}}, \quad (\text{B2})$$

where  $O_{Q10}$  is an ecosystem-specific  $Q_{10}$  coefficient (Table 1);  $T_{\text{SOIL}}(z, t)$  is the hourly soil temperature at depth  $z$  (centimeters) and time  $t$  (hours), which is simulated by the STM module for each 1 cm depth of the soil; and  $T_{\text{OR}}$  is the reference soil temperature ( $^{\circ}\text{C}$ ) that varies with vegetation type (Table 1).

### B3. Effects of Soil Moisture on Methanotrophy

[52] A variety of studies indicate that soil moisture is a predictor of methane oxidation rate [e.g., *Steudler et al.*, 1989; *Gulledge and Schimel*, 1998]. However, some recent modeling efforts have not considered the importance of this factor to methanotrophy [e.g., *Walter and Heimann*, 2000; *Zhang et al.*, 2002]. Here we assume that the effect of soil moisture on methane oxidation is similar to the effect of soil moisture on decomposition of soil organic carbon [see *Tian et al.*, 1999]. Therefore we model the influence of volumetric soil moisture on methanotrophic microbial activity as

$$f(E_{\text{SM}}(z, t)) = \frac{(M_V - M_{V\min})(M_V - M_{V\max})}{[(M_V - M_{V\min})(M_V - M_{V\max})] - (M_V - M_{V\text{opt}})^2}, \quad (\text{B3})$$

where  $M_{V\min}$ ,  $M_{V\text{opt}}$ , and  $M_{V\max}$  are the minimum, optimum, and maximum volumetric soil moistures for the methanotrophic reaction, respectively, which vary among ecosystems (Table 1);  $M_V$  is the soil moisture at each 1 cm depth of the soil, which is estimated by the HM.

### B4. Effects of Redox Potential on Methanotrophy

[53] Redox potential ( $E_{HL}$ ) is used to model the relative availability of electron acceptors (e.g.,  $\text{O}_2$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Fe}^{+3}$ ,  $\text{Mn}^{+4}$ ) on methane oxidation. Oxygen in the soil is the primary electron acceptor for this process [Segers, 1998]. However, methane oxidation may still occur under anaerobic conditions (i.e.,  $E_{HL}$  less than 300 mV), if alternative electron acceptors are available. To simulate these effects, we use the relationship between redox potential and methane oxidation described by *Zhang et al.* [2002],

$$f(R_{OX}(z, t)) = 0.0 \quad E_{HL}(z, u) < -200 \text{ mV}, \quad (\text{B4})$$

$$f(R_{OX}(z, t)) = \beta \times E_{HL}(z, u) + 1.5 \quad -100 \text{ mV} \geq E_{HL}(z, u) \geq -200 \text{ mV}, \quad (\text{B5})$$

$$f(R_{OX}(z, t)) = \gamma \times E_{HL}(z, u) + \frac{5}{6} \quad 200 \text{ mV} \geq E_{HL}(z, u) > -100 \text{ mV}, \quad (\text{B6})$$

$$f(R_{OX}(z, t)) = 1.0 \quad E_{HL}(z, u) > 200 \text{ mV}, \quad (\text{B7})$$



where  $f(R_{\text{OX}}(z, t))$  is the effect of redox potential at depth  $z$  (centimeters) and time  $t$  (hours);  $E_{\text{HL}}(z, u)$  is the estimated daily redox potential at depth  $z$  and day  $u$ ; and  $\beta$  and  $\gamma$  are constants, which equal  $0.0075 \text{ mV}^{-1}$  and  $8.3 \times 10^{-4} \text{ mV}^{-1}$ , respectively. The calculation of daily changes in  $E_{\text{HL}}(z, u)$  is described in section A3 of Appendix A.

## Appendix C: Methane Transport

[54] The atmosphere, vegetation, and soils are treated as a continuum for the movement of methane from soils to the atmosphere. Transport of methane from soils to the atmosphere can occur via three different pathways: diffusion, plant-aided emissions, and ebullition. In upland soils, we assume that diffusion of atmospheric methane into soils is the sole method of moving methane through the soil. However, in wetland soils, we assume that all three pathways are important. Here we describe, in more detail, how we estimate the transport of methane through these pathways and how they influence our estimates of methane fluxes between the soil and the atmosphere.

### C1. Methane Diffusion

[55] We assume that diffusion of methane occurs throughout the soil profile based on the concentration gradient of methane within the soil following Fick's law through coarse soil pores,

$$F_D(z, t) = -D(z) \frac{\partial C_M(z, t)}{\partial z}, \quad (\text{C1})$$

where  $F_D(z, t)$  is the diffusive flux at depth  $z$  (centimeters) and time  $t$  (hours), and  $C_M(z, t)$  is the corresponding methane concentration ( $\mu\text{mol L}^{-1}$ ). The diffusion coefficient,  $D(z)$  in units of  $\text{cm}^2 \text{ h}^{-1}$ , is modeled as

$$D(z) = 0.66 \times D_i \times f(\text{coarse}), \quad (\text{C2})$$

where 0.66 is the tortuosity coefficient, suggesting that the distance covered by diffusion is about two thirds of the length of the real average path;  $D_i$  is the molecular diffusion coefficient of methane, which is  $0.2 \text{ cm}^2 \text{ s}^{-1}$  in unsaturated soil layers and  $0.00002 \text{ cm}^2 \text{ s}^{-1}$  in saturated soil layers [Walter and Heimann, 2000]; and  $f(\text{coarse})$  is the relative volume of the coarse pores. The difference in  $D_i$  between the unsaturated and saturated soil layers reflects the difference in the rate of molecular diffusion of methane through air versus water; we do not consider potential effects of soil moisture on hindrance diffusion under saturated conditions. In addition to tortuosity and soil moisture, the diffusion of methane through soil depends on soil porosity [Dörr *et al.*, 1993], which is a function of soil texture. To account for the influence of porosity, the factor  $f(\text{coarse})$  is calculated as

$$f(\text{coarse}) = \text{SAND} \times \text{PV}_{\text{SAND}} + \text{SILT} \times \text{PV}_{\text{SILT}} + \text{CLAY} \times \text{PV}_{\text{CLAY}}, \quad (\text{C3})$$

where SAND, SILT, and CLAY represent the relative contents of sand, silt, and clay (%) in the soil, which are prescribed for a site; and  $\text{PV}_{\text{SAND}}$ ,  $\text{PV}_{\text{SILT}}$ , and  $\text{PV}_{\text{CLAY}}$

denote the relative volume of coarse pores in sandy, silty, and clayish soils, respectively. These latter parameters are set to 0.45, 0.20, and 0.14, respectively, following Walter *et al.* [2001a]. The  $F_D(z, t)$  for each 1 cm depth can be deduced simultaneously from equation (C1) and equation (1) using the Crank-Nicolson method [Press *et al.*, 1990]. For boundary conditions, the  $\text{CH}_4$  concentration change at the lower boundary ( $L_B$ ) is set to zero and the  $\text{CH}_4$  concentration at the soil surface (or water surface if the water table is at or above the soil surface) is set to  $0.076 \mu\text{mol L}^{-1}$  to represent the atmospheric  $\text{CH}_4$  concentration. Diffusion from only the surface soil layer contributes to methane emissions to the atmosphere or to the consumption of atmospheric methane by soils as  $F_D(z = 0, t)$ .

### C2. Plant-Aided Transport

[56] The root systems of some plants also provide a more direct conduit for methane produced at depth in the soil to reach the atmosphere. As described by Walter and Heimann [2000], the rate at which methane is removed from a soil layer at depth  $z$  (centimeters) and time  $t$  (hours) through vegetation roots,  $R_P(z, t)$  is modeled as a function of the quality of plant-mediated transport at a site ( $\text{TR}_{\text{VEG}}$ ), the distribution of roots in the soil, the growth stage of vegetation during the growing season, and the distribution of soil methane concentrations ( $C_M(z, t)$ ) in the soil,

$$R_P(z, t) = K_P \text{TR}_{\text{VEG}} f_{\text{ROOT}}(z) f_{\text{GROW}}(t) C_M(z, t), \quad (\text{C4})$$

where  $K_P$  is a rate constant of  $0.01 \text{ h}^{-1}$ ;  $f_{\text{ROOT}}(z)$  is a multiplier that describes the effects of the relative amount of root biomass at depth  $z$  (centimeters); and  $f_{\text{GROW}}(t)$  is a multiplier that describes the effect of growth stage at time  $t$  (hours). The term  $\text{TR}_{\text{VEG}}$  depends on vegetation type and plant density. Because we assume that trees do not contribute to plant-aided transport, we set  $\text{TR}_{\text{VEG}}$  equal to 0.0 for boreal forests. As grasses and sedges, which are similar to tussock tundra, are good gas transporters [Walter, 1998] and shrubs are very poor gas transporters [Walter and Heimann, 2000], we set  $\text{TR}_{\text{VEG}}$  equal to 0.5 for tundra ecosystems that we consider to be a mosaic of tussock and shrub tundra. The density of roots is assumed to decrease linearly with depth. Thus the  $f_{\text{ROOT}}(z)$  multiplier is determined as follows:

$$f_{\text{ROOT}}(z) = 2 \times \left(1 - \frac{z}{R_D}\right) \quad z \leq R_D \quad (\text{C5a})$$

$$f_{\text{ROOT}}(z) = 0.0 \quad z > R_D, \quad (\text{C5b})$$

where  $R_D$  is the rooting depth (centimeters), which is determined from vegetation type and soil texture [Vörösmarty *et al.*, 1989]. Similar to Walter and Heimann [2000], we also assume that the ability of plants to conduct methane varies with the life history of the plant, with the maximum conductance of methane occurring in mature plants. To simulate the effect of growth stage on  $R_P(z, t)$ , we calculate  $f_{\text{GROW}}(t)$  based on an assumed relationship

between leaf area index (LAI) and soil temperatures ( $T_{S20}$ ) described by *Walter and Heimann*, [2000],

$$f_{\text{GROW}}(t) = \text{LAI}_{\min} \quad T_{S20} < T_{\text{gr}}, \quad (\text{C6a})$$

$$f_{\text{GROW}}(t) = \text{LAI}_{\min} + \text{LAI}_{\max} \left( 1 - \left( \frac{T_{\text{mar}} - T_{S20}}{T_{\text{mat}} - T_{\text{gr}}} \right)^2 \right) \quad (\text{C6b})$$

$$T_{\text{gr}} \leq T_{S20} \leq T_{\text{mat}},$$

$$f_{\text{GROW}}(t) = \text{LAI}_{\max} \quad T_{\text{mat}} < T_{S20}, \quad (\text{C6c})$$

where  $\text{LAI}_{\min}$  is the minimum LAI associated with the beginning of plant growth;  $\text{LAI}_{\max}$  is the maximum LAI associated with plants at maturity;  $T_{\text{gr}}$  is the temperature at which plants start to grow; and  $T_{\text{mat}}$  is the temperature at which plants reach maturity during the growing season. Similar to *Walter and Heimann* [2000],  $\text{LAI}_{\min}$  and  $\text{LAI}_{\max}$  have been chosen to be 0 and 4, respectively;  $T_{\text{gr}}$  is equal to 2°C where the annual mean soil temperature is below 5°C, and otherwise,  $T_{\text{gr}}$  is equal to 7°C; and  $T_{\text{mat}}$  is assumed to equal  $T_{\text{gr}} + 10^\circ\text{C}$ . However, unlike *Walter and Heimann* [2000], we have chosen to use the mean soil temperature across the top 20 cm of the soil profile to represent  $T_{S20}$  rather than the temperature at the 50 cm depth. Our previous studies [Zhuang *et al.*, 2002, 2003] have demonstrated that using the mean soil temperature of the top 20 cm of the soil profile, which roughly represents the organic soil layer, is more useful for determining seasonal soil carbon and nitrogen dynamics.

[57] A few studies [e.g., *Schipper and Reddy*, 1996; *Gerard and Chanton*, 1993] have indicated that methane may be oxidized in the small oxic zone around root tips, although the proportion of methane that is oxidized by this pathway is highly uncertain. We assume that 40% of the methane in plant-mediated transport is oxidized before the gas reaches the atmosphere, which is less than the 50% oxidized assumed by *Walter and Heimann* [2000]. The methane emissions transported through the plant-mediated pathway to the atmosphere is obtained integrating  $R_p(z, t)$  over the soil profile from the rooting depth to the soil surface as

$$F_p(t) = \int_{R_D}^0 R_p(z, t) dz. \quad (\text{C7})$$

### C3. Methane Ebullition

[58] The formation of bubbles in the soil profile allows methane to be transported through the soil more rapidly than would be predicted by diffusion alone. Following *Walter and Heimann* [2000], the loss of methane through bubbles ( $R_E(z, t)$ ) from a soil layer at depth  $z$  (centimeters) and time  $t$  (hours) is modeled as a function of soil  $\text{CH}_4$  concentrations  $f(C_M(z, t))$ ,

$$R_E(z, t) = K_e f(C_M(z, t)), \quad (\text{C8a})$$

if  $z$  is below the water table, and

$$R_E(z, t) = 0.0, \quad (\text{C8b})$$

if  $z$  is above the water table.  $K_e$  is a rate constant of  $1.0 \text{ h}^{-1}$ . If the methane concentration  $C_M(z, t)$  is greater than a threshold for bubble formation ( $M_{\text{TH}}$ ),  $f(C_M(z, t))$  is equal to the difference between  $C_M(z, t)$  and  $M_{\text{TH}}$ ; otherwise,  $f(C_M(z, t))$  is equal to 0.0. A value of  $500 \mu\text{mol L}^{-1}$  is assumed to represent  $M_{\text{TH}}$  [Walter and Heimann, 2000] for all the ecosystems in our study. From the soil layers below the water table depth, bubbles are assumed to reach the water table within 1 hour. If the water table is at or above the soil surface, ebullition is assumed to contribute to methane emissions to the atmosphere as  $F_E(t)$ , which is obtained by integrating  $R_E(z, t)$  over the whole water saturated zone,

$$F_E(t) = \int_{L_B}^{W_T} R_E(z, t) dz, \quad (\text{C9a})$$

if  $W_T$  is at or above the soil surface, and

$$F_E(t) = 0.0, \quad (\text{C9b})$$

if  $W_T$  is below the soil surface, where  $W_T$  is the depth of the water table (centimeters); and  $L_B$  is the lower boundary of the soil (centimeters). If the water table is below the soil surface, the methane in bubbles is added to the methane concentration in the soil layer just above the water table. This methane then continues to diffuse upward through the soil profile. In this case,  $F_E(t)$  equals 0.0.

## Appendix D: Updated Hydrological Module

[59] The hydrological module (HM) [Zhuang *et al.*, 2002] has been revised to be appropriate for both upland and wetland soils. The revisions include improvements in the simulation of infiltration ( $I_F$ ), evapotranspiration of the vegetation canopy ( $E_V$ ), soil surface evaporation ( $E_S$ ), snowmelt ( $S_{\text{melt}}$ ), and sublimation ( $S_S$ ) from the snowpack. In addition, soil moisture dynamics are represented in greater detail for upland soils, and algorithms, based on work by *Granberg et al.* [1999], have been added to simulate water content and water table depth in wetland soils.

### D1. Infiltration From the Soil Surface Into the Soil ( $I_F$ )

[60] The liquid water from rain throughfall or snowmelt either infiltrates into the soil column or is lost as surface runoff. In the work of *Zhuang et al.* [2002], all liquid water reaching the soil surface has been assumed to infiltrate into the soil column. In this study, we add algorithms to estimate surface runoff and subtract this estimate from rain throughfall and snowmelt to estimate infiltration ( $I_F$ ). Following *Bonan* [1996], surface runoff is calculated using the Dunne runoff if the soil surface is saturated or the Horton runoff if the soil surface is not saturated. In the Dunne approach, all the water inputs at the surface (i.e., rain throughfall and snowmelt) are lost as

runoff because the soil is already saturated. In the Horton approach, runoff occurs even when the soil is not saturated, but the total water inputs at the surface are greater than the infiltration capacity, which depends on the water content of the surface soil layer relative to the saturated water content of this layer.

## D2. Evapotranspiration From the Vegetation Canopy ( $E_V$ )

[61] In *Zhuang et al.* [2002], we simulated evapotranspiration by simulating transpiration and evaporation from the canopy with separate algorithms. In the updated HM, we have replaced these algorithms with those of *McNaughton and Jarvis* [1983], which are based on the Penman-Monteith approach. Evapotranspiration from the vegetation canopy ( $E_V$ ) is estimated based on short-wave solar radiation absorbed by the vegetation canopy, air temperature, vapor pressure deficit, and canopy conductance. The amount of solar radiation absorbed by the canopy is determined using the incident short-wave solar radiation occurring at the top of the canopy and the leaf area index (LAI) of the vegetation [*Zhuang et al.*, 2002].

[62] Following *Rosenberg et al.* [1983], vapor pressure deficit is modeled as

$$\text{VPD} = 10 \times (E_{\text{adt}} - V_P), \quad (\text{D1})$$

where  $V_P$  is vapor pressure (kPa) from input data sets.  $E_{\text{adt}}$  is saturation vapor pressure (kPa),

$$E_{\text{adt}} = 0.61078 \times e^{\frac{17.269 \times T_A}{T_A + 237.3}}, \quad (\text{D2})$$

where  $T_A$  is air temperature ( $^{\circ}\text{C}$ ).

[63] A simplified equation of *Waring and Running* [1998] has been adopted to model the canopy water conductance ( $G$ ),

$$G = g_{\text{max}} f(T_A) f(\text{VPD}) f(\psi), \quad (\text{D3})$$

where  $g_{\text{max}}$  is the maximum canopy conductance ( $\text{mm s}^{-1}$ );  $f(T_A)$  is a multiplier that describes the effect of air temperature ( $T_A$ ) on the canopy conductance;  $f(\text{VPD})$  is a multiplier that describes the effect of the vapor pressure deficit (VPD in mbar) on canopy conductance; and  $f(\psi)$  is a multiplier that describes the effect of leaf water potential (lwp in MPa) on canopy conductance. We set  $g_{\text{max}}$  to be 3.5, 13.5, and 21.2  $\text{mm s}^{-1}$  for alpine tundra, wet tundra, and boreal forests, respectively. The effects of air temperature on canopy conductance are calculated following *Thornton* [2000],

$$f(T_A) = 0.0 \quad T_A < -8.0^{\circ}\text{C}, \quad (\text{D4a})$$

$$f(T_A) = 1.0 + \eta \times T_A \quad -8.0^{\circ} < T_A < 0.0^{\circ}\text{C}, \quad (\text{D4b})$$

$$f(T_A) = 1.0 \quad T_A > 0.0^{\circ}\text{C}, \quad (\text{D4c})$$

where  $\eta$  is a constant ( $0.125^{\circ}\text{C}^{-1}$ ). The effects of vapor pressure deficit on canopy conductance are calculated as

$$f(\text{VPD}) = 0.0 \quad \text{VPD} > \text{VPD}_{\text{close}}, \quad (\text{D5a})$$

$$f(\text{VPD}) = \frac{\text{VPD}_{\text{close}} - \text{VPD}}{\text{VPD}_{\text{close}} - \text{VPD}_{\text{open}}} \quad \text{VPD}_{\text{open}} < \text{VPD} < \text{VPD}_{\text{close}}, \quad (\text{D5b})$$

$$f(\text{VPD}) = 1.0 \quad \text{VPD} < \text{VPD}_{\text{open}}, \quad (\text{D5c})$$

where  $\text{VPD}_{\text{close}}$  is the vapor pressure deficit at complete conductance reduction and  $\text{VPD}_{\text{open}}$  is the vapor pressure deficit at the start of canopy conductance reduction. We assume  $\text{VPD}_{\text{close}}$  is 41.0 mbar and  $\text{VPD}_{\text{open}}$  is 9.3 mbar for all vegetation types.

[64] The effects of leaf water potential (lwp) on canopy conductance are calculated in a similar manner,

$$f(\psi) = 0.0 \quad \text{lwp} < \psi_{\text{close}}, \quad (\text{D6a})$$

$$f(\psi) = \frac{\psi_{\text{close}} - \text{lwp}}{\psi_{\text{close}} - \psi_{\text{open}}} \quad \psi_{\text{close}} < \text{lwp} < \psi_{\text{open}}, \quad (\text{D6b})$$

$$f(\psi) = 1.0 \quad \text{lwp} > \psi_{\text{open}}, \quad (\text{D6c})$$

where  $\psi_{\text{close}}$  is the leaf water potential at complete conductance reduction and  $\psi_{\text{open}}$  is the leaf water potential at the start of conductance reduction. We assume that  $\psi_{\text{close}}$  is  $-2.3$  MPa and  $\psi_{\text{open}}$  is  $-0.6$  MPa for all vegetation types. As in the work of *Zhuang et al.* [2002], lwp is calculated as

$$\text{lwp} = \frac{0.2}{W_S / \text{SOIL}_{\text{CAP}}}, \quad (\text{D7})$$

where  $W_S$  is mean daily soil water content (millimeters) integrated across the soil profile from the upper boundary to the lower boundary, and  $\text{SOIL}_{\text{CAP}}$  is a parameter for soil water capacity (millimeters) of the soils, which is set to 235 [see *Zhuang et al.*, 2002].

## D3. Evaporation From the Soil Surface ( $E_S$ )

[65] The evaporation rate from the soil surface is modeled using the Penman approach [*Zhuang et al.*, 2002], which uses air temperature, vapor pressure deficit, short-wave solar radiation at the soil surface, and the throughfall of rain from the overlying vegetation canopy. In the work of *Zhuang et al.* [2002], a mean daily rate of potential evaporation is estimated for a month and a monthly rate is determined by multiplying this mean daily rate by the number of days per month ( $M_D$ ). In this study, we use the daily potential evaporation ( $\text{PE}_S$ ) estimates directly (i.e.,  $M_D = 1.0$ ) when calculating daily evaporation from the soil surface ( $E_S$ ). If the daily throughfall of rain ( $R_{\text{TH}}$ ) is greater



than or equal to  $PE_S$ , then  $E_S$  is assumed to equal  $PE_S$ ; otherwise,  $E_S$  is equal to  $R_{TH}$ .

#### D4. Snowmelt ( $S_{melt}$ ) and Snow Sublimation ( $S_S$ )

[66] The rate of snowmelt has been modeled by *Zhuang et al.* [2002], using monthly shortwave solar radiation, throughfall of snow from the overlying vegetation canopy, snow albedo, and the number of days per month. The potential snowmelt rate ( $PS_{melt}$  in millimeters) now uses a daily time step, which depends on daily air temperature and solar radiation [*Brubaker et al.*, 1996; Edward Rastetter, personal communication, 2002],

$$PS_{melt} = m_q \times \left( \frac{R_n/100.0}{0.2388} \right) + A_R \times T_A, \quad (D8)$$

where  $m_q$  is a constant ( $2.99 \text{ kg MJ}^{-1}$ ),  $R_n$  is the incident short-wave solar radiation to the snowpack ( $\text{J cm}^{-2} \text{ d}^{-1}$ ),  $A_R$  is a constant ( $2.0 \text{ mm } ^\circ\text{C}^{-1} \text{ d}^{-1}$ ), and  $T_A$  is the daily air temperature ( $^\circ\text{C}$ ). If the daily throughfall of snow is greater than  $PS_{melt}$ , then  $S_{melt}$  is equal to  $PS_{melt}$ ; otherwise  $S_{melt}$  is equal to the daily throughfall of snow.

[67] The rate of snow sublimation has also been modeled by *Zhuang et al.* [2002] based on monthly short-wave solar radiation and throughfall of snow from the overlying vegetation canopy. In the work of *Zhuang et al.* [2002], a mean potential sublimation rate is determined and multiplied by the number of days per month ( $M_D$ ) to obtain a monthly rate. In this study, we use the potential daily sublimation rate ( $PS_S$ ) directly (i.e.,  $M_D = 1.0$ ) based on daily shortwave solar radiation. If the  $PS_S$  is greater than water equivalent of the snowpack, then  $S_S$  is assumed to equal the water equivalent of the snowpack; otherwise  $S_S$  is assumed to equal  $PS_S$ .

#### D5. Upland Soils

[68] In the work of *Zhuang et al.* [2002], the soil profile has been represented with three soil layers: a moss or litter layer, an organic soil layer, and a mineral soil layer. Changes to the water content of the whole soil profile ( $W_S$  in millimeters) have depended on infiltration ( $I_F$ ), evapotranspiration from the vegetation canopy ( $E_V$ ), evaporation from the soil surface ( $E_S$ ), and drainage from the deep mineral layer ( $D_R$ ),

$$\frac{dW_S}{dt} = I_F - E_V - E_S - D_R. \quad (D9)$$

Within each soil layer, changes in water content have been determined using a water balance approach similar to that described in equation (D9). The terms  $I_F$  and  $D_R$  are replaced by percolation into and out of a soil layer, respectively, and  $E_S$  is assumed to occur only from the top moss or litter layer. Only the organic soil and mineral soil layers are assumed to contribute to  $E_V$ , and this flux has been partitioned between the two layers based upon the relative soil water content of the two layers. Soil moisture has been assumed to be uniformly distributed within each of the three soil layers.

[69] To improve our simulation of water dynamics in upland soils in high-latitude ecosystems, we now repre-

sent the soil profile with six layers with different hydrologic characteristics: a 10-cm-thick moss or litter layer, a 20-cm-thick upper organic soil layer, a 40-cm-thick lower organic soil layer, an 80-cm-thick upper mineral soil layer, a 160-cm-thick lower mineral soil layer, and a 320-cm-thick deep mineral soil layer. We assume that all upland soils have the same soil profile structure for our soil water dynamics due to a lack of spatially explicit data sets for each grid cell. Changes to the water content of the entire soil profile are still influenced by the factors given in equation (D9). However, soil moistures within each of the six layers are now assumed to vary as described by the Richards equation [*Hillel*, 1980; *Celia et al.*, 1990],

$$\frac{\partial W_C}{\partial t} = \frac{\partial}{\partial z} \left( k \left( \frac{\partial W_C}{\partial z} \frac{\partial \psi_s}{\partial W_C} + 1 \right) \right), \quad (D10)$$

where  $W_C$  is the volumetric water content ( $\text{mm}^3 \text{ mm}^{-3}$ );  $k$  is the hydraulic conductivity ( $\text{mm s}^{-1}$ ); and  $\psi_s$  is the soil matrix potential (millimeters), which varies as a function of  $W_C$  and soil texture [*Clapp and Hornberger*, 1978]. The soil water content ( $W_C$ ) for the midpoint of each of the different layers of the unsaturated soils is obtained simultaneously through solving equations (D9) and (D10) numerically with a tridiagonal system of equations [see *Press et al.*, 1990]. Infiltration ( $I_F$ ) into the first soil layer sets the upper boundary condition for the numerical solution and the drainage ( $D_R$ ) of the deep mineral soil layer, which is equal to the hydraulic conductivity of this layer, sets the lower boundary condition. Although the Richards equation could be used to estimate soil moistures at each 1 cm depth in the profile, large amounts of computation time would be required to extrapolate this approach across the Pan-Arctic. Instead, we use the soil moisture contents at the midpoints of each of the six soil layers to interpolate soil moistures at each 1 cm depth across the soil profile.

#### D6. Wetland Soils

[70] Because *Zhuang et al.* [2002] only considered water dynamics in unsaturated soils, new algorithms needed to be developed to estimate the proportion of the soil profile that becomes saturated, the depth of the resulting water table, and the influence of the water table on soil moisture in the unsaturated portion of the soil profile. We assume that wetland soils are always saturated below 30 cm, which represents the maximum water table depth ( $z_b$ ). Thus changes in water content ( $W_S$ ) of the top 30 cm of the soil profile can be calculated with a water balance model that considers the water input and outputs at the daily time step,

$$\frac{dW_S}{dt} = I_F - E_V - E_S - Q_{DR}, \quad (D11)$$

where  $I_F$  is infiltration,  $E_V$  is evapotranspiration of the vegetation canopy,  $E_S$  is evaporation from the soil surface, and  $Q_{DR}$  is the saturated flow drainage below  $z_b$ . Calculation of the  $I_F$ ,  $E_V$ , and  $E_S$  terms for wetlands use the same algorithms that have been described in the

previous sections of Appendix D. Similar to *Walter et al.* [2001a],  $Q_{DR}$  is calculated as

$$Q_{DR} = Q_{DRMAX} \times f(\text{coarse}), \quad (D12)$$

where  $Q_{DRMAX}$  is the maximum drainage rate of 20 mm d<sup>-1</sup>; and  $f(\text{coarse})$  is the relative volume of coarse pores in the soil. The calculation of  $f(\text{coarse})$  is described in equation (C3).

[71] Instead of the six layers used to simulate upland soils, we assume that water dynamics in wetland soils can be represented by two functional layers or “zones”: an upper oxygenated, unsaturated zone; and a lower anoxic, saturated zone. The water table represents the boundary between these two zones, and its depth is allowed to change over time with changes in soil moisture. The maximum thickness of the upper unsaturated layer is represented by the maximum water table depth ( $z_b$ ), which is assumed to be 30 cm [Frolking et al., 1996; Granberg et al., 1999]. The minimum thickness of the lower saturated layer is the difference between the depth of the lower boundary ( $L_B$ ) and 30 cm. The total volume of water in the top 30 cm of the soil profile ( $V_{TOT}$  in centimeters) is represented by

$$V_{TOT} = \phi(z_b - W_T) + \int_{W_T}^0 \theta_{us}(z) dz, \quad (D13)$$

where  $\phi$  is the soil porosity,  $W_T$  is the actual water table depth (centimeters), and  $\theta_{us}(z)$  is the volumetric water content in the unsaturated zone at depth  $z$ . We assume  $\phi$  is equal to 0.9 cm<sup>3</sup> cm<sup>-3</sup> [Frolking and Crill, 1994] for the entire soil profile. If  $W_S$  is greater than  $z_b \times \phi$ , the water table will be above the soil surface and the height of water above the soil surface is determined by the difference of  $W_S$  and  $z_b \times \phi$ . Otherwise,  $V_{TOT}$  is equal to  $W_S$ . After setting  $V_{TOT}$  to equal  $W_S$ , equation (D13) can be integrated and inverted to solve for the water table depth ( $W_T$ ) following Granberg et al. [1999],

$$W_T = \sqrt{\frac{3(\phi \times z_b - W_W)}{2a_z}} \quad z \leq z_{\theta s, \min} \quad (D14a)$$

$$W_T = \frac{3(\phi \times z_b - W_W)}{2(\phi - \theta_{s, \min})} \quad z > z_{\theta s, \min}, \quad (D14b)$$

where  $a_z$  is the gradient in soil moisture resulting from evaporation at the soil surface and is calculated as the ratio of  $\phi - \theta_{s, \min}$  to  $z_{\theta s, \min}$ ;  $\theta_{s, \min}$  is the minimum volumetric water content at the soil surface; and  $z_{\theta s, \min}$  is the maximum depth where evaporation influences soil moisture. We assume  $\theta_{s, \min}$  is 0.25 and  $z_{\theta s, \min}$  is 10 cm for all wetland soils. A negative value of the water table depth indicates that the water table is above the soil surface, whereas a positive value indicates that the water table is below the soil surface.

[72] After determining the water table depth, the volumetric water content at each 1 cm depth can then be estimated. If depth  $z$  is in the saturated zone, the volumetric water content is assumed to be equal to  $\phi$ . If depth  $z$  is in the

unsaturated zone, the volumetric water content ( $\theta_{us}(z)$ ) is estimated following Granberg et al. [1999],

$$\theta_{us}(z) = \min \left( \phi, \theta_s + (\phi - \theta_s) \left( \frac{z}{W_T} \right)^2 \right), \quad (D15)$$

where  $\theta_s$  is the volumetric water content at the soil surface and is calculated as

$$\theta_s = \max(\theta_{s, \min}, \phi - (a_z \times W_T)). \quad (D16)$$

## Notation

|  |   |
|--|---|
| $\phi$                                     | soil porosity in wetlands (cm <sup>3</sup> cm <sup>-3</sup> ).  |
| $\alpha, \eta, \beta, \text{ and } \gamma$ | constants as $-0.01 \text{ mV}^{-1}$ , $0.125 \text{ } ^\circ\text{C}^{-1}$ , $0.0075 \text{ mV}^{-1}$ , $8.3 \times 10^{-4} \text{ mV}^{-1}$ , respectively. |
| $\Psi_{\text{close}}, \Psi_{\text{open}}$  | leaf water potential at complete conductance reduction (MPa), leaf water potential at the start of conductance reduction (MPa).                               |
| $\Psi_S$                                   | soil matrix potential (mm).   |
| $\theta_s$                                 | volumetric water content at the soil surface (cm <sup>3</sup> cm <sup>-3</sup> ).   |
| $\theta_{s, \min}$                         | minimum volumetric water content of the soil surface (cm <sup>3</sup> cm <sup>-3</sup> ).   |
| $\theta_{us}(z)$                           | volumetric water content in the unsaturated zone at depth $z$ (cm <sup>3</sup> cm <sup>-3</sup> ).  |
| $A_L$                                      | plant aerenchyma factor.  |
| $A_R$                                      | constant for calculating snow-melt (mm $^\circ\text{C}^{-1} \text{ d}^{-1}$ ).  |
| $a_z$                                      | gradient in soil moisture resulting from evaporation at the soil surface.   |
| $C_M(z, t)$                                | soil CH <sub>4</sub> concentrations at depth $z$ and time $t$ (μmol L <sup>-1</sup> ).  |
| $C_R$                                      | change rate of soil redox potential under saturation conditions (100 mV).   |
| $D(z)$                                     | diffusion coefficient of methane (mol cm <sup>-2</sup> h <sup>-1</sup> ).   |
| $D_i$                                      | molecular diffusion coefficient of methane in bulk air or in the saturated water soils (cm <sup>2</sup> s <sup>-1</sup> ).                                    |
| $D_R$                                      | drainage from the deep mineral layer in the upland soils (mm d <sup>-1</sup> ).   |
| $E_{HL}(z, u)$                             | redox potential at soil depth $z$ (mV) and day $u$ .  |
| $E_V$                                      | evapotranspiration of the vegetation canopy (mm d <sup>-1</sup> ).  |
| $f(\psi)$                                  | multiplier that describes the effects of leaf water potential on canopy water conductance.  |

|                            |  |  |   |
|----------------------------|--|--|---|
| $f(C_{\text{DIS}}(z))$     | multiplier that describes the relative availability of organic carbon substrate at depth $z$ in the soils.                               | $f_{\text{GROW}}(t)$   | multiplier that describes the effects of the growing stage of vegetation on plant-aided $\text{CH}_4$ transport.                              |
| $f(C_M(z, t))$             | multiplier that describes the effects of soil $\text{CH}_4$ concentrations on methanotrophy at depth $z$ and time $t$ .                  | $F_P(t)$   | plant-aided $\text{CH}_4$ emissions at time $t$ ( $\mu\text{mol h}^{-1}$ ).   |
| $f(\text{coarse})$         | relative volume of the coarse pores in the soils (%).  | $f_{\text{ROOT}}(z)$   | multiplier that describes the effects of the vertical distribution of roots in the soils at depth $z$ on plant-aided $\text{CH}_4$ transport. |
| $f(E_{\text{SM}}(z, t))$   | multiplier that describes the effects of soil moisture on methanotrophy at depth $z$ and time $t$ .                                      | $F_W(z)$   | fraction of water filled pore space ( $\text{mm}^3 \text{mm}^{-3}$ ).   |
| $f(M_{\text{ST}}(z, t))$   | multiplier that describes the effects of soil temperature on methanogenesis at depth $z$ and time $t$ .                                  | $G$  | canopy water conductance ( $\text{mm s}^{-1}$ ).  |
| $f(\text{pH}(t))$          | multiplier that describes the effects of soil water pH on methanogenesis at time $t$ .   | $g_{\text{max}}$   | maximum canopy water conductance ( $\text{mm s}^{-1}$ ).  |
| $f(R_{\text{OX}}(z, t))$   | multiplier that describes the effects of soil redox potentials on methanotrophy at depth $z$ and time $t$ .                              | $I_F$  | water infiltration ( $\text{mm d}^{-1}$ ).  |
| $f(R_X(z, t))$             | multiplier that describes the effects of redox potentials on methanogenesis at depth $z$ and time $t$ .                                  | $K$  | hydraulic conductivity of the soils ( $\text{mm s}^{-1}$ ).   |
| $f(S_{\text{OM}}(t))$      | multiplier that describes the effects of methanogenic substrate availability on methanogenesis at time $t$ .                             | $K_{\text{CH}_4}$  | ecosystem-specific half saturation constant used in Michaelis-Menten kinetics of methane oxidation process ( $\mu\text{mol L}^{-1}$ ).        |
| $f(T_A)$                   | multiplier that describes the effects of air temperature on canopy water conductance.  | $K_e$  | rate constant for $\text{CH}_4$ ebullitive transport ( $\text{h}^{-1}$ ).   |
| $f(T_{\text{SOIL}}(z, t))$ | multiplier that describes the effects of soil temperature on methanotrophy at depth $z$ and time $t$ .                                   | $K_p$  | rate constant for plant-aided $\text{CH}_4$ transport ( $\text{h}^{-1}$ ).  |
| $f(\text{VPD})$            | multiplier that describes the effects of the vapor pressure deficit on canopy water conductance.   | $\text{LAI}_{\text{min}}, \text{LAI}_{\text{max}}$               | constants used for calculating the growing state of the plants ( $\text{m}^2 \text{m}^{-2}$ ).  |
| $F_{\text{CA}}$            | cross-section area of a typical fine root ( $\text{m}^2$ ).  | $L_B$  | lower boundary of the modeled soil profile (cm).  |
| $F_{\text{CH}_4}(t)$       | total flux of methane at the soil/water-atmosphere boundary via the different transport pathways at time $t$ ( $\mu\text{mol h}^{-1}$ ). | $L_{\text{MAXB}}$  | prescribed maximum lower boundary (cm).   |
| $F_D(z, t)$                | diffusive flux of $\text{CH}_4$ through the soil layer at depth $z$ and time $t$ ( $\mu\text{mol h}^{-1}$ ).                             | $\text{lwp}$   | leaf water potential (MPa).   |
| $F_D(z = 0, t)$            | diffusive flux at the interface between the soil surface and the atmosphere at time $t$ ( $\mu\text{mol h}^{-1}$ ).                      | $M_D$  | number of days within a month.  |
| $F_E(t)$                   | ebullitive $\text{CH}_4$ emissions at time $t$ ( $\mu\text{mol h}^{-1}$ ).   | $M_{\text{GO}}$  | ecosystem-specific maximum potential $\text{CH}_4$ production rate ( $\mu\text{mol L}^{-1} \text{h}^{-1}$ ).                                  |
|                            |  | $M_O(z, t)$  | soil $\text{CH}_4$ oxidation rate at depth $z$ and time $t$ ( $\mu\text{mol L}^{-1} \text{h}^{-1}$ ).   |
|                            |  | $M_P(z, t)$  | soil $\text{CH}_4$ production rate at depth $z$ and time $t$ ( $\mu\text{mol L}^{-1} \text{h}^{-1}$ ).  |
|                            |  | $m_q$  | constant used for calculating snow sublimation from the snowpack ( $2.99 \text{ kg MJ}^{-1}$ ).   |
|                            |  | $M_{\text{TH}}$  | threshold concentration for bubble formation ( $\mu\text{mol L}^{-1}$ ).  |
|                            |  | $M_{\text{vmax}}, M_{\text{vmin}}, \text{ and } M_{\text{vopt}}$ | Maximum, minimum, and optimum volumetric soil moisture for methanotrophy ( $\text{mm}^3 \text{mm}^{-3}$ ).                                    |
|                            |  | $\text{NPP}(\text{mon})$   | monthly net primary productivity ( $\text{g C m}^{-2} \text{month}^{-1}$ ).   |
|                            |  | $\text{NPP}_{\text{MAX}}$  | maximum monthly net primary productivity (NPP) for a particular ecosystem ( $\text{g C m}^{-2} \text{month}^{-1}$ ).                          |



|                                   |   |  |   |
|-----------------------------------|---|--|---|
| $O_{MAX}$                         | ecosystem-specific maximum oxidation coefficient ( $\mu\text{mol L}^{-1} \text{h}^{-1}$ ).  | $TR_{VEG}$                                 | multiplier that describes the effect of vegetation type and plant density on plant-aided $\text{CH}_4$ transport.                               |
| $O_{Q10}$                         | ecosystem-specific $Q_{10}$ coefficient indicating the soil temperature dependency of methanotrophy.  | $T_{S20}$                                  | soil temperature across the top 20 cm of the soils ( $^{\circ}\text{C}$ ).  |
| $P_A$                             | scalar used to indicate the degree of gas diffusion from plant roots to the atmosphere in plant-aided $\text{CH}_4$ transport.                                      | $T_{SOIL}(z, t)$                           | soil temperature at depth $z$ and time $t$ ( $^{\circ}\text{C}$ ).  |
| $pH_{MIN}, pH_{MAX}, pH_{OPT}$    | minimum, maximum, and optimum soil pH, respectively for methanogenesis.   | $V_P$                                      | vapor pressure (kPa).   |
| $P_{Q10}$                         | ecosystem-specific $Q_{10}$ coefficient indicating the dependency of $\text{CH}_4$ production to soil temperature.  | VPD  | vapor pressure deficit (mbar).  |
| $PV_{SAND}, PV_{SILT}, PV_{CLAY}$ | relative volumes of coarse pores in sandy, silty, and clayish soils, respectively ( $\text{mm}^3 \text{mm}^{-3}$ ).   | VPD <sub>close</sub> , VPD <sub>open</sub> | vapor pressure deficit at complete conductance reduction (mbar) and vapor pressure deficit at the start of canopy conductance reduction (mbar). |
| $Q_{DR}$                          | saturated flow drainage below the maximum water table depth ( $\text{mm d}^{-1}$ ).   | $V_{TOT}$                                  | total amount of water in the top 30 cm of the soil profile in wetlands (cm).  |
| $Q_{DRMAX}$                       | maximum drainage rate below the maximum water table depth ( $\text{mm d}^{-1}$ ).   | $W_C$                                      | volumetric water content ( $\text{mm}^3 \text{mm}^{-3}$ ).  |
| $R_D$                             | rooting depth (cm).   | $W_S$                                      | mean daily soil water content integrated across the soil profile from the upper boundary to the lower boundary (mm).                            |
| $R_E(z, t)$                       | soil $\text{CH}_4$ ebullitive emissions rate at depth $z$ and time $t$ ( $\mu\text{mol L}^{-1} \text{h}^{-1}$ ).  | $W_T$                                      | water table depth (cm).   |
| $R_{LD}$                          | fine root length density ( $\text{m root m}^{-3}$ soil).  | $z_{0,min}$                                | maximum depth where evaporation influences soil moisture (cm).  |
| $R_n$                             | incident shortwave solar radiation at the top of the canopy ( $\text{J cm}^{-2} \text{d}^{-1}$ ).   | $z_b$                                      | maximum water table depth (cm).   |
| $R_P(z, t)$                       | plant-aided $\text{CH}_4$ emissions rate at depth $z$ and time $t$ ( $\mu\text{mol L}^{-1} \text{h}^{-1}$ ).  |  |   |
| SAND, SILT, and CLAY              | relative contents of sand, silt, and clay, respectively, in soil(%).  |  |   |
| $S_{melt}$                        | snowmelt rate ( $\text{mm d}^{-1}$ ).   |  |   |
| SOIL <sub>CAP</sub>               | water capacity of the soils (mm).   |  |   |
| $S_S$                             | rate of sublimation from the snowpack ( $\text{mm d}^{-1}$ ).   |  |   |
| $T_A$                             | daily air temperature ( $^{\circ}\text{C}$ ).   |  |   |
| $T_{gr}$                          | temperature at which plants start to grow ( $^{\circ}\text{C}$ ).   |  |   |
| $T_{mat}$                         | temperature at which plants reach maturity ( $^{\circ}\text{C}$ ).  |  |   |
| $T_{OR}$                          | ecosystem-specific reference soil temperature used in the $Q_{10}$ function for simulating the effects of soil temperature on methanotrophy ( $^{\circ}\text{C}$ ). |  |   |
| $T_{PR}$                          | ecosystem-specific reference temperature used in the $Q_{10}$ function for simulating the effects of soil temperature on methanogenesis ( $^{\circ}\text{C}$ ).     |  |   |

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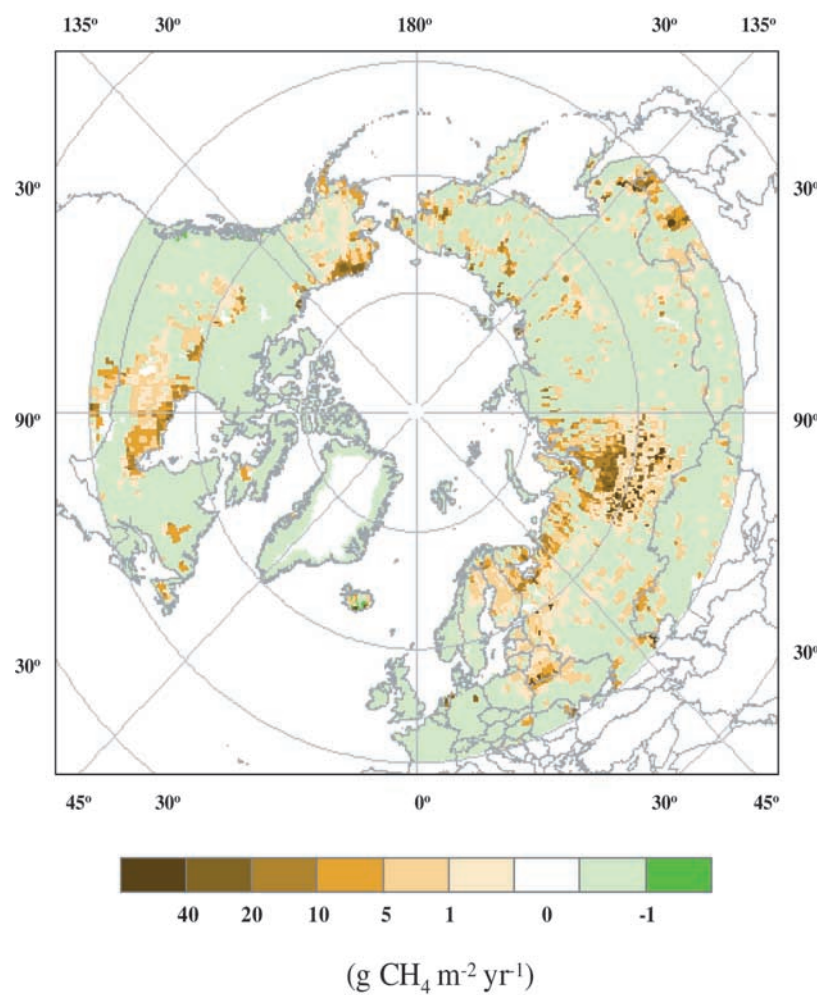
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**Figure 3.** Simulated net CH<sub>4</sub> emissions and consumption in the Pan-Arctic region during the 1990s. Positive values indicate the net CH<sub>4</sub> release to the atmosphere, and negative values indicate the CH<sub>4</sub> uptake from the atmosphere.